

# Efficient and Perfectly Unlinkable Sanitizable Signatures without Group Signatures

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**Abstract.** Sanitizable signatures allow for controlled modification of signed data. The essential security requirements are accountability, privacy and unlinkability. Unlinkability is a strong notion of privacy. Namely, it makes it hard to link two sanitized messages that were derived from the same message-signature pair. In this work, we strengthen the standard unlinkability definition by *Brzuska* et al. at PKC '10, making it robust against malicious or buggy signers. While state-of-the art schemes deploy costly group signatures to achieve unlinkability, our construction uses standard digital signatures, which makes them compatible with existing infrastructure.

We construct a sanitizable signature scheme that satisfies the strong notion of perfect unlinkability and, simultaneously, achieves the strongest notion of accountability, i.e., non-interactive public accountability. Our construction is not only legally compliant, but also highly efficient, as the measurements of our reference implementation show. Finally, we revisit the security model by *Canard* et al. and correct a small flaw in their security definition given at AfricaCrypt '12.

## 1 Introduction

Sanitizable signature schemes (**SanSigs**), introduced by *Ateniese* et al. [3], enable a designated party, the sanitizer, to alter a signed document in a controlled way. The sanitizer (holding its own sanitizer secret) can generate a new, yet valid, signature for the modified document without interacting with the signer of the original document. In particular, let the message  $m$  consists of  $\ell$  blocks, i.e.,

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$m = (m[1], \dots, m[\ell])$ , where  $\ell \in \mathbb{N}$  and  $m[i] \in \{0, 1\}^*$ . Then, the sanitizer is only able to modify those blocks  $m[i]$  that the signer defined as admissible. Sanitization thus yields a new message-signature pair  $(m', \sigma')$ , where  $\sigma'$  is a valid signature for  $m'$  under the signer's public key  $pk_{\text{sig}}$  and  $m'$  is equal to  $m$  on all *non*-admissible blocks.

**Motivation.** Malleable signatures of this kind seem to bear an inherent risk: a semi-trusted party is allowed to change signed data and thus a signer gives up control over the statements that are produced in its name. However, when carefully implemented, delegation of signing rights turns out to be very useful for a variety of application scenarios, ranging from sanitizing medical records to secure routing and blank signatures [3, 9, 22, 23]. Another application scenario is access control for databases. In any larger company, but in particular in banks and hospitals, access policies are inherent in day-to-day operations [39]. Compliance rules in banks actually enforce the separation of different sectors, and likewise, hospitals host large databases of sensitive data that must not be accessed by anybody. The reception desk personnel in a hospital, for example, must not be able to access medical data of a patient, while the accountant of the hospital, in turn, must not learn personally identifying details of the patient. On the other hand, integrity of the database is crucial for both, hospitals and banks, and besides appropriate read-and-write policies [39], one might aim for the cryptographic protection of, say, patient records and have them digitally signed by the treating personnel. The accountant and the receptionist then both access different parts of an authenticity protected record. Hence, some entries in the signed record need to be sanitized while keeping a valid signature over the rest of the record. Whereas standard signatures do not allow for such modifications, sanitizable signatures enable to implement privacy-friendly access and integrity verifiability simultaneously. In particular, using sanitizable signatures, the database can operate without repeated interaction with the signer (the medical personnel). In a bank, interaction with the signer might even be disallowed, e.g., due to money laundering policies. To sum up, we aim for signatures that allow for controlled modification of different parts of a signed document without interaction with the original signer.

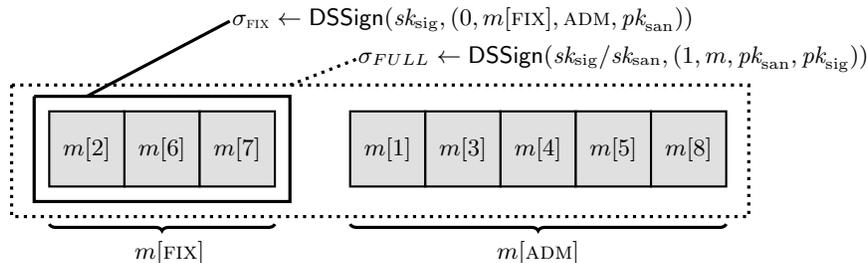
Sanitizable signatures usually strive for strong privacy guarantees to hide the removed sensitive information. The strongest notion of privacy is unlinkability, which we review next. In the hospital database example, we derive two different sanitized documents from the original patient's record, as we removed different parts from the same signed patient record to create a version for the accountant and another one for the reception desk personnel. A secure solution must prevent inferring information about the original record by combining the two sanitized documents, as this would violate the patient's privacy concerns as well as data-protection regulations such as HIPAA [15]. Thus, in such application domains [10], it is important for sanitizable signatures schemes to achieve unlinkability.

A digital signature on a document usually provides a legal value of evidence [34]. For example, in a hospital, the medical personnel sign their entries in the database and can be held accountable for those later, i.e., the signature allows for identifying the doctor or nurse that generated an entry. For **SanSigs** there are two different options for accountability: interactive accountability involves the signer and allows an authority to trace back the origin of a message-signature pair, while the scheme itself might be transparent, i.e., the origin of a signature is hidden from third-parties<sup>1</sup>. The alternative is a non-interactive public form of accountability [11] where third-parties can identify immediately whether the medical record was sanitized or not without interaction with the signer. As observed by *Pöhls* and *Höhne* [34], current legislation only attributes a high value of evidence to sanitizable signature if *any* subsequent change can be detected, which is incompatible with the property of transparency. Formally, *Brzuska* et al. show how to achieve public accountability in the absence of transparency, as the two are mutually exclusive [11]. In turn, privacy and a public, i.e., non-interactive, form of accountability can be achieved simultaneously, as *Brzuska* et al. [11] show. We continue this line of practical research and strengthen the privacy by achieving perfect unlinkability with standard primitives.

**Challenges and Contributions.** In a nutshell, our scheme addresses the following challenges: (1) Strong privacy guarantees, namely perfect unlinkability and perfect privacy, (2) a high legal value of evidence through non-interactive public accountability, (3) compatibility with existing public key infrastructures (PKI) for standard signatures, (4) performance restrictions for economic applicability. From a practitioner’s point of view, having a legally recognizable *and* extremely efficient scheme is essential for deployment of a signature scheme [35, 36]. Our scheme is based on the ideas given in [9, 11]. It extends their work in the aforementioned points. Essentially, we achieve stronger privacy and accountability properties with simpler building blocks. Moreover, we are also able to consider unlinkability and strengthen the original definition from *Brzuska* et al. from PKC ’10 [10] to be more robust against malicious or buggy signers, as well as corruption of the signer’s key. Interestingly, the new definition turns out to be more compact than the original one, as the oracles that use the signer’s secret key can now be simulated by the adversary. Hence, the **Sign** and the **Proof** oracle of [10] are not required anymore. We also correct a small flaw in the security definition of unlinkability in the multi-sanitizer setting given by *Canard* et al. at AfricaCrypt ’12 [13]. There, the **LoRSanit**-oracle does not check whether *both* inputs are valid message-signature pairs and whether the requested modification is admissible. Thus, as we show, the original definition is not achievable. Finally, we show how to switch on-the-fly between unlinkability and linkability.

**Techniques.** The first sanitizable signature scheme [3] was based on chameleon hashes [28] that were applied per each admissible block. However, their construction allowed for mix-and-match attacks. Later schemes had to find a collision on

<sup>1</sup> third-parties here meaning other than signer or sanitizer



**Fig. 1.** Blocks 2,6,7 of  $m$  are fixed and together with  $pk_{san}$  and ADM signed by signer ( $\sigma_{FIX}$ ). The complete message  $m$  is signed by either the signer or the sanitizer ( $\sigma_{FULL}$ ).

each admissible blocks, not only those modified [8]. Thereby, the sanitizing process was linear in the number of admissible blocks. Some later constructions [10, 9, 11] were based on a different paradigm. The idea is to use two signatures (see Fig. 1); one to sign the fix part of  $m$ , i.e.,  $m[FIX]$ , we sometimes call this the “inner signature”, and another one to sign the admissible parts, i.e.,  $m[ADM]$ , together with the fixed parts, often called the “outer signature”. The inner signature is produced by the signer of the signature scheme, while the outer signature can be produced by either one, the signer or the sanitizer. Using different signature types as inner and outer signature yields different properties of the sanitizable signature scheme. For instance, *Brzuska et al.* [10] use a group signature for the outer signature. The anonymity of the group signature makes signatures of the signer and the sanitizer indistinguishable, and the non-frameability/traceability property of the group signature scheme assures an interactive form of accountability. In turn, in [9] and [11], the authors use standard signature schemes also for the outer signature. The scheme becomes very efficient; it is not transparent anymore, but it still enjoys privacy [9, 11] and a non-interactive public form of accountability [11], thus complying with legal standards. As transparency is sometimes seen as a stronger notion of privacy, one might feel that one has to compromise, as one cannot obtain a strong notion of accountability and a strong notion of privacy simultaneously. We show that this is actually not the case. As the inner signature scheme, we use a deterministic signature scheme and prove that the scheme satisfies both, a public, non-interactive version of accountability and a statistical notion of unlinkability, the strongest notion of privacy. At the same time, we maintain high efficiency and compatibility with existing public-key infrastructure, as our scheme only requires a constant number of standard building block operations. Our construction is even less complex than the ones given in [41], as we do not deploy labels. This makes our scheme applicable for use on Smart Cards [35], embedded devices like routers, or other devices which do not have as much processing power. All of these requirements are of paramount importance to make SanSigs used in practice.

**State-of-the-Art and Related Work.** Malleable signatures scheme have gained a lot of attention in the past few years. They were studied in several flavors, for example, redactable signature schemes [16, 25, 32, 33, 40], sanitizable signatures with several extensions [9, 12, 18, 22, 27, 30, 36, 42] and combinations of both approaches [24]. Moreover, the integrity protection of structured data, such as in [7, 29, 37, 38], has equally been studied in the recent past. All schemes aim at the same goal: allowing for controlled modification of signed data to preserve privacy, while retaining authentication of origin and integrity protection against uncontrolled, i.e., unauthorized, modifications. In this paper, we focus on sanitizable signatures, as introduced by *Ateniese et al.* [3]. They also introduced the aforementioned security properties for sanitizable signatures, namely privacy, immutability, accountability, transparency and unforgeability. These were later formalized and extended by *Brzuska et al.* [8, 10]. Their framework has been extended to multi-sanitizer environments by *Canard et al.* [13]. We work within the original framework for a single signer and a single sanitizer and show in Sect. 4 how to modify our scheme to the multi-user setting from [13].

The stronger notion of *statistical* unlinkability for *redactable* signature schemes was introduced by *Ahn et al.* at TCC '12 [1], and even stronger notions have been discussed recently in [4, 5, 19]. Neither of these notions has been considered in the context of sanitizable signatures yet, and we address this gap. The schemes for *quoting* substrings [1, 4, 5] are tailored towards achieving both, statistical transparency and statistical unlinkability. This ambitious goal comes at the price of weakening the unforgeability property to selective unforgeability in the case of [1]. Additionally, none of the mentioned schemes is accountable. By trading in transparency, our construction does not only achieve stronger notions of unlinkability and accountability, but also the standard adaptive unforgeability notion instead of selective unforgeability. In the context of sanitizable signatures, the notion of unlinkability captures that two sanitized *messages* cannot be linked to having the same original *message-signature pair*. For group signatures [17], in turn, the unlinkability definition corresponds to the anonymity of the signer, which is usually called transparency in the context of sanitizable signatures. The different nomenclature is maybe best explained by the fact that discussions in the area of malleable signatures are message-centered, while the way of thinking in the area of group signatures is more signer-centered—after all, the word “group” refers to a group of signers, not to a group of messages. To avoid confusion due to the historical evolution of the properties’ names in the two areas, we stress that the present paper uses the nomenclature as introduced in [10]. Another related concept are proxy signatures [31]. However, they allow for delegating signing rights entirely, while sanitizable signatures allow for *altering* a specific signed message.

## 2 Security Models

### 2.1 Syntax and Notation

For a message  $m = (m[1], \dots, m[\ell])$ , we call  $m[i] \in \{0, 1\}^*$  a *block*, while the special symbol “,”  $\notin \{0, 1\}^*$  denotes a uniquely reversible concatenation of strings. The special symbol  $\perp \notin \{0, 1\}^*$  denotes an error or an exception. The following nomenclature is adapted from *Brzuska et al.* [8], who address a setting of single signers and sanitizers. We also elaborate in Sect. 4 on how to extend our construction for multi-sanitizer environments as described by *Canard et al.* [13].

**Definition 1 (Sanitizable Signature Scheme).** *Any SanSig consists of at least seven efficient, i.e., PPT algorithms. In particular, let  $\text{SanSig} := (\text{KGen}_{sig}, \text{KGen}_{san}, \text{Sign}, \text{Sanit}, \text{Verify}, \text{Proof}, \text{Judge})$ , such that:*

**Key Generation.** *There are two key generation algorithms, one for the signer and one for the sanitizer. Both create a pair of keys, a private key and the corresponding public key, based on the security parameter  $\lambda$ :*

$$(\text{pk}_{sig}, \text{sk}_{sig}) \leftarrow \text{KGen}_{sig}(1^\lambda) \quad (\text{pk}_{san}, \text{sk}_{san}) \leftarrow \text{KGen}_{san}(1^\lambda)$$

**Signing.** *The Sign algorithm takes as input the security parameter  $\lambda$ , a message  $m = (m[1], \dots, m[\ell])$ ,  $m[i] \in \{0, 1\}^*$ , the secret key  $\text{sk}_{sig}$  of the signer, the public key  $\text{pk}_{san}$  of the sanitizer, as well as a description ADM of the admissibly modifiable blocks. In detail, ADM contains a set of indices of the modifiable blocks and the overall number  $\ell$  of blocks in  $m$ , to guard against length-altering attacks. The Sign algorithm outputs the message  $m$  and a signature  $\sigma$  (or  $\perp$ , indicating an error):*

$$(m, \sigma) \leftarrow \text{Sign}(1^\lambda, m, \text{sk}_{sig}, \text{pk}_{san}, \text{ADM})$$

**Sanitizing.** *The algorithm Sanit takes a message  $m = (m[1], \dots, m[\ell])$ , where  $m[i] \in \{0, 1\}^*$ , a signature  $\sigma$ , the security parameter  $\lambda$ , the public key  $\text{pk}_{sig}$  of the signer and the secret key  $\text{sk}_{san}$  of the sanitizer. It modifies the message  $m$  according to the modification instruction MOD, which contains pairs  $(i, m[i]')$  describing the index  $i$  and the blocks new value  $m[i]'$ . We use the shorthand notation of  $m' \leftarrow \text{MOD}(m)$  to denote that the modification instructions were successfully applied to create the modified  $m'$  from  $m$ . Note, MOD could also be empty, i.e.,  $m' = m$  is generally possible. Sanit calculates a new signature  $\sigma'$  for the modified message  $m' \leftarrow \text{MOD}(m)$ . The Sanit algorithm outputs  $m'$  and  $\sigma'$  (or possibly  $\perp$  in case of an error).*

$$(m', \sigma') \leftarrow \text{Sanit}(1^\lambda, m, \text{MOD}, \sigma, \text{pk}_{sig}, \text{sk}_{san})$$

**Verification.** *The algorithm Verify outputs a decision  $d \in \{0, 1\}$  verifying the correctness of a signature  $\sigma$  for a message  $m = (m[1], \dots, m[\ell])$ ,  $m[i] \in \{0, 1\}^*$  with respect to the public keys  $\text{pk}_{sig}$  and  $\text{pk}_{san}$  and the security parameter  $\lambda$ :*

$$d \leftarrow \text{Verify}(1^\lambda, m, \sigma, \text{pk}_{sig}, \text{pk}_{san})$$

**Proof.** The algorithm *Proof* takes as input the security parameter, the secret signing key  $\text{sk}_{sig}$ , a message  $m = (m[1], \dots, m[\ell])$ ,  $m[i] \in \{0, 1\}^*$  and a signature  $\sigma$  as well a set of (polynomially bounded) additional message-signature pairs  $\{(m_i, \sigma_i) \mid i \in \mathbb{N}\}$  and the public key  $\text{pk}_{san}$ . The *Proof* algorithm outputs a string  $\pi \in \{0, 1\}^*$  (or  $\perp$ , indicating an error):

$$\pi \leftarrow \text{Proof}(1^\lambda, \text{sk}_{sig}, m, \sigma, \{(m_i, \sigma_i) \mid i \in \mathbb{N}\}, \text{pk}_{san})$$

**Judge.** The algorithm *Judge* takes as input the security parameter, a message  $m = (m[1], \dots, m[\ell])$ ,  $m[i] \in \{0, 1\}^*$  and a valid signature  $\sigma$ , the public keys of the parties and a proof  $\pi$ . The *Judge* algorithm outputs a decision  $d \in \{\text{Sig}, \text{San}, \perp\}$  indicating whether the message-signature pair has been created by the signer or the sanitizer (or  $\perp$ , indicating an error):

$$d \leftarrow \text{Judge}(1^\lambda, m, \sigma, \text{pk}_{sig}, \text{pk}_{san}, \pi)$$

We require that for every *SanSig* the usual correctness properties hold. That is, for every genuinely created message-signature pair created by the *Sign* algorithm, the *Verify* algorithm outputs 1 with overwhelming probability. From every message-signature pair with a positive verification result, the *Sanit* algorithm produces again a message-signature pair for which the *Verify* algorithm outputs 1 with overwhelming probability. The latter is recursive, i.e., sanitized message-signature pairs can be sanitized again. For every genuinely generated value of the proof  $\pi$ , the *Judge* algorithm outputs the correct party, i.e., *Sig* or *San*, with overwhelming probability. For more details on the definition of correctness, refer to [8]. In case of a *SanSig* with non-interactive public accountability, the *Proof* algorithm always returns  $\perp$ , and *Judge* correctly decides upon such an empty proof ( $\pi = \perp$ ) with overwhelming probability.

We write  $m[\text{ADM}]$  for the uniquely reversible concatenation of the *admissible* blocks and  $m[\text{FIX}]$  for the uniquely reversible concatenation of the *fixed* blocks in the order of appearance in  $m$ . Note, we do not attach any labels to the blocks as done in [41]. We require the public key to be efficiently derivable from its corresponding secret key. Additionally, we require that ADM is always correctly recoverable from any valid signature  $\sigma$ , which accounts for the findings by [21].

## 2.2 Security of Sanitizable Signatures

We present an extended security model based on [8]. It covers the basic ideas and features of a *SanSig*.

*Experiment Privacy* $_{\mathcal{A}}^{\text{SanSig}}(\lambda)$   
 $(pk_{\text{sig}}, sk_{\text{sig}}) \leftarrow \text{KGen}_{\text{sig}}(1^\lambda)$   
 $(pk_{\text{san}}, pk_{\text{san}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $b \leftarrow \{0, 1\}$   
 $a \leftarrow \mathcal{A}_{\text{Proof}(sk_{\text{sig}}, \dots), \text{Sanit}(\dots, sk_{\text{san}})}^{\text{Sign}(sk_{\text{sig}}, \dots), \text{LoRSanit}(\dots, sk_{\text{sig}}, sk_{\text{san}}, b)}(pk_{\text{sig}}, pk_{\text{san}})$   
 where oracle **LoRSanit** on input of:  
 $m_{0,i}, \text{MOD}_{0,i}, m_{1,i}, \text{MOD}_{1,i}, \text{ADM}_i$   
 if  $\text{MOD}_{0,i} \not\subseteq \text{ADM}_i$ , return  $\perp$   
 if  $\text{MOD}_{1,i} \not\subseteq \text{ADM}_i$ , return  $\perp$   
 if  $\text{MOD}_{0,i}(m_{0,i}) \neq \text{MOD}_{1,i}(m_{1,i})$ , return  $\perp$   
 let  $(m_i, \sigma_i) \leftarrow \text{Sign}(m_{b,i}, sk_{\text{sig}}, pk_{\text{san}}, \text{ADM}_i)$   
 return  $(m'_i, \sigma'_i) \leftarrow \text{Sanit}(m_i, \text{MOD}_{b,i}, \sigma, pk_{\text{sig}}, sk_{\text{san}})$   
 return 1, if  $a = b$

**Fig. 2.** Privacy

*Experiment Transparency* $_{\mathcal{A}}^{\text{SanSig}}(\lambda)$   
 $(pk_{\text{sig}}, sk_{\text{sig}}) \leftarrow \text{KGen}_{\text{sig}}(1^\lambda)$   
 $(pk_{\text{san}}, sk_{\text{san}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $b \leftarrow \{0, 1\}$   
 $a \leftarrow \mathcal{A}_{\text{Proof}(sk_{\text{sig}}, \dots), \text{Sanit}(\dots, sk_{\text{san}})}^{\text{Sign}(sk_{\text{sig}}, \dots), \text{Sanit/Sign}(\dots, sk_{\text{sig}}, sk_{\text{san}}, b)}(pk_{\text{sig}}, pk_{\text{san}})$   
 where oracle **Sanit/Sign** for input  $m_i, \text{MOD}_i, \text{ADM}_i$   
 let  $(m_i, \sigma_i) \leftarrow \text{Sign}(1^\lambda, m_i, sk_{\text{sig}}, pk_{\text{san}}, \text{ADM}_i)$ ,  
 compute  $(m'_i, \sigma'_i) \leftarrow \text{Sanit}(m_i, \text{MOD}_i, \sigma_i, pk_{\text{sig}}, sk_{\text{san}})$   
 if  $b = 1$ :  
 compute  $(m'_i, \sigma'_i) \leftarrow \text{Sign}(m'_i, sk_{\text{sig}}, pk_{\text{san}}, \text{ADM}_i)$   
 finally return  $(m'_i, \sigma'_i)$   
 return 1 if  $a = b$  and  $\mathcal{A}$  has not queried  
 any  $(m_i, \sigma_i)$  output by **Sanit/Sign** to **Proof**.

**Fig. 3.** Transparency

*Experiment Unlinkability* $_{\mathcal{A}}^{\text{SanSig}}(\lambda)$   
 $(pk_{\text{sig}}, sk_{\text{sig}}) \leftarrow \text{KGen}_{\text{sig}}(1^\lambda)$   
 $(pk_{\text{san}}, pk_{\text{san}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $b \leftarrow \{0, 1\}$   
 $a \leftarrow \mathcal{A}_{\text{Proof}(sk_{\text{sig}}, \dots), \text{Sanit}(\dots, sk_{\text{san}})}^{\text{Sign}(sk_{\text{sig}}, \dots), \text{LoRSanit}(\dots, sk_{\text{san}}, sk_{\text{sig}}, b)}(pk_{\text{sig}}, pk_{\text{san}})$   
 where oracle **LoRSanit** on input of:  
 $m_{0,i}, \text{MOD}_{0,i}, \sigma_{0,i}, m_{1,i}, \text{MOD}_{1,i}, \sigma_{1,i}$   
 //ADM needs to be recoverable from all  $\sigma$   
 if  $\text{ADM}_{0,i} \neq \text{ADM}_{1,i}$ , return  $\perp$   
 if  $\text{MOD}_{0,i} \not\subseteq \text{ADM}_{0,i}$ , return  $\perp$   
 if  $\text{MOD}_{1,i} \not\subseteq \text{ADM}_{1,i}$ , return  $\perp$   
 if  $\text{MOD}_{0,i}(m_{0,i}) \neq \text{MOD}_{1,i}(m_{1,i})$ , return  $\perp$   
 if  $\text{Verify}(1^\lambda, m_{0,i}, \sigma_{0,i}, pk_{\text{sig}}, pk_{\text{san}}) \neq 1$  or  
 $\text{Verify}(1^\lambda, m_{1,i}, \sigma_{1,i}, pk_{\text{sig}}, pk_{\text{san}}) \neq 1$ , return  $\perp$   
 return  $(m', \sigma') \leftarrow \text{Sanit}(m_{b,i}, \text{MOD}_{b,i}, \sigma_{b,i}, pk_{\text{sig}}, sk_{\text{san}})$   
 return 1, if  $a = b$

**Fig. 4.** Unlinkability by *Brzuska* et al.

*Experiment Unlinkability* $_{\mathcal{A}}^{\text{SanSig}}(\lambda, n, m)$   
 $(\text{PK}, \text{SK}) \leftarrow \text{Setup}(1^\lambda, n, m)$   
 $b \leftarrow \{0, 1\}$   
 $(m_0, \text{MOD}_0, \sigma_0, m_1, \text{MOD}_1, \sigma_1, j_0, j_1, st) \leftarrow \mathcal{A}_{\text{ch}}^{\text{ch}}(\text{PK})$   
 let  $(m', \sigma') \leftarrow \text{Sanit}(m_b, \sigma_b, \text{SK}_{[j_b]}, \text{MOD}_b, \text{PK})$   
 let  $(\text{ORI}, I_{\text{ORI}}, \pi_{\text{ORI}}) \leftarrow \text{FindOri}(m', \sigma', \text{osk}_{\text{ORI}}, \text{PK})$   
 if  $I_{\text{ORI}} = 0$  or  $(I_{\text{ORI}} = (\text{Sig}, i_{\text{ORI}})$  and  $i_{\text{ORI}} \in \mathcal{CU})$  or  
 $j_0 \in \mathcal{CU}$  or  $j_1 \in \mathcal{CU}$  or  
 $\text{Judge}(m', \sigma', (\text{ORI}, i_{\text{ORI}}, \pi_{\text{ORI}}), \text{PK}) = 0$ , return  $\perp$   
 let  $b^* \leftarrow \mathcal{A}_{\text{gu}}^{\text{gu}}(m', \sigma', st)$   
 if  $(m', \sigma')$  was queried to **SigOpen**, return  $\perp$ , else  $b^*$

**Fig. 5.** Unlinkability by *Canard* et al.

*Experiment SUnlinkability* $_{\mathcal{A}}^{\text{SanSig}}(\lambda)$   
 $(pk_{\text{san}}, sk_{\text{san}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $b \leftarrow \{0, 1\}$   
 $a \leftarrow \mathcal{A}_{\text{Sanit}(\dots, sk_{\text{san}}), \text{LoRSanit}(\dots, sk_{\text{san}}, b)}^{\text{Sanit}(\dots, sk_{\text{san}})}(pk_{\text{san}})$   
 where oracle **LoRSanit** on input of:  
 $m_{0,i}, \text{MOD}_{0,i}, \sigma_{0,i}, m_{1,i}, \text{MOD}_{1,i}, \sigma_{1,i}, pk_{\text{sig},i}$   
 //ADM needs to be recoverable from all  $\sigma$   
 if  $\text{ADM}_{0,i} \neq \text{ADM}_{1,i}$ , return  $\perp$   
 if  $\text{MOD}_{0,i} \not\subseteq \text{ADM}_{0,i}$ , or  $\text{MOD}_{1,i} \not\subseteq \text{ADM}_{1,i}$ , or  $\text{MOD}_{0,i}(m_{0,i}) \neq \text{MOD}_{1,i}(m_{1,i})$ , return  $\perp$   
 if  $\text{Verify}(1^\lambda, m_{0,i}, \sigma_{0,i}, pk_{\text{sig},i}, pk_{\text{san}}) \neq 1$  or  $\text{Verify}(1^\lambda, m_{1,i}, \sigma_{1,i}, pk_{\text{sig},i}, pk_{\text{san}}) \neq 1$ , return  $\perp$   
 return  $(m', \sigma') \leftarrow \text{Sanit}(m_{b,i}, \text{MOD}_{b,i}, \sigma_{b,i}, pk_{\text{sig},i}, sk_{\text{san}})$   
 return 1, if  $a = b$

**Fig. 6.** Strengthened Unlinkability

**Definition 2 (Privacy).** A sanitizable signature scheme *SanSig* is private, if for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{Privacy}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 2 returns 1, is negligibly close to  $\frac{1}{2}$  (as a function of  $\lambda$ ). Here, the

adversary must be able to decide which input was chosen by the LoRSanit. The oracle signs and sanitizes the data itself.

**Definition 3 (Transparency).** A sanitizable signature scheme *SanSig* is transparent, if for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{Transparency}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 3 returns 1, is negligibly close to  $\frac{1}{2}$  (as a function of  $\lambda$ ). Here, the oracle either directly signs the expected output message ( $b = 1$ ) or signs the input and then sanitizes it to the expected output ( $b = 0$ ).

Please note, in accordance with Brzuska et al. [8], we require that  $\text{MOD}_i \subseteq \text{ADM}_i$  is true. We check this for all queries to the above oracles as otherwise a trivial attack vector exists. In particular, if  $\text{MOD}_i \not\subseteq \text{ADM}_i$  yields that *Sanit* outputs  $\perp$  then this is easily distinguishable from a “fresh” signature.

**Definition 4 (Strengthened Unlinkability following Brzuska et al.).** A sanitizable signature scheme *SanSig* is unlinkable, if for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{SUnlinkability}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 6 returns 1 is negligibly close to  $\frac{1}{2}$  (as a function of  $\lambda$ ). Here, the adversary has to guess which of the two inputted message-signature pairs was chosen to be sanitized.

Compare our new definition of unlinkability in Fig. 6 with the original definition of [10] depicted in Fig. 4. We altered the LoRSanit oracle so that it does not specify the signer by having a fixed signer key  $pk_{\text{sig}}$ . In turn, now, the adversary chooses  $pk_{\text{sig}}$ . Intuitively, this captures that unlinkability holds as long as the sanitizer is honest, even if the signer happens to be dishonest. One might argue that a malicious signer can always break any privacy or unlinkability property, as it knows which messages it signed and thus, it can always recover the originally signed message. However, there exist intermediary stages, for example, if the signer is buggy, uses weak randomness, or loses its secret key. In these cases, our definition turns out to be robust, i.e., even if the signer loses its secret key, unlinkability and therefore privacy are preserved. In a sense, we cover the equivalent of forward secrecy for the case of key exchange: there, previous sessions remain secure when long-term secrets are lost [14].

Actually, we even achieve a stronger notion of secrecy than key exchange can attain. Unlinkability is even preserved when the signer loses his secret key *before* signing the message and even when using some form of “bad” secret key specified by the adversary. In Def. 4, there are no signing and proof oracles—the reason is that the adversary can now simulate those by itself. We now prove that our new notion of unlinkability is strictly stronger than the original one by Brzuska et al. [10].

**Theorem 1.** Any strongly unlinkable *SanSig* is also unlinkable. The converse is not true.

*Proof.* Let *SanSig* be a strongly unlinkable sanitizable signature scheme. We prove via reduction that *SanSig* is also unlinkable. Let  $\mathcal{A}$  be an adversary against the unlinkability of *SanSig*. Using  $\mathcal{A}$ , we can construct an adversary  $\mathcal{B}$  against the strong unlinkability of *SanSig* as follows. In the beginning of the game,  $\mathcal{B}$

relays the sanitizer’s public key to  $\mathcal{A}$  and runs the key generation algorithm of the signer and returns the signer’s public key  $pk_{\text{sig}}$  to  $\mathcal{A}$ . The signer’s secret key is used to answer all queries that  $\mathcal{A}$  makes to **Sign** and **Proof**. The remaining queries are queries to the **Sanit** oracle, which  $\mathcal{B}$  simply relays, and queries to the **LoRSanit** oracle which  $\mathcal{B}$  prepends with the signer’s public key  $pk_{\text{sig}}$  and queries to its own **LoRSanit** oracle. In the end,  $\mathcal{A}$  returns a bit that  $\mathcal{B}$  returns as well. As the simulation is perfect,  $\mathcal{B}$ ’s advantage against strong unlinkability is as big as  $\mathcal{A}$ ’s advantage against unlinkability.

We now separate the two unlinkability notions by constructing a (contrived) scheme that fulfills the security requirements of the original security model by Brzuska et al. [10] but is insecure in our new model.

Let  $\text{SanSig} = (\text{KGen}_{\text{sig}}, \text{KGen}_{\text{san}}, \text{Sign}, \text{Sanit}, \text{Verify}, \text{Proof}, \text{Judge})$  be a secure sanitizable signature scheme. To obtain a counterexample, we adjust the scheme as follows:

- $\text{KGen}'_{\text{sig}}$  works as  $\text{KGen}_{\text{sig}}$ , except that it appends a 1 to the public key returned by  $\text{KGen}_{\text{sig}}$
- $\text{KGen}'_{\text{san}}$  works as its original counterpart
- $\text{Judge}'$ ,  $\text{Sign}'$ , and  $\text{Verify}'$  work as their original counterparts, but cut off the last bit of  $pk_{\text{sig}}$
- $\text{Sanit}'$  is the same as **Sanit** with one exception: if  $pk_{\text{sig}}$  ends with a 0, it proceeds as normal, while cutting off the last bit of  $pk_{\text{sig}}$ . Otherwise, it outputs the *original* signature and message, instead of sanitizing it.

Our stronger attacker, that can choose  $pk_{\text{sig}}$  by running  $\text{KGen}'_{\text{sig}}$ , now wins by replacing the trailing 1 with a 0. However, the scheme is fully secure in the original definition where an attacker was not able to influence  $pk_{\text{sig}}$ . Here, it does not matter, if the keys are indistinguishable. All other properties are not affected and are inherited from the original **SanSig**. Note, this scheme is also still correct as the message-signature pair left untouched by the modified  $\text{Sanit}'$  still verifies, while also  $\text{MOD}_1(m_1) = \text{MOD}_2(m_2)$  yields.

As our stronger notion of unlinkability implies the original notion of unlinkability, all known implications still hold. In particular, our strengthened unlinkability also implies privacy [10].

**Definition 5 (Unlinkability by Canard et al.).** *A sanitizable signature scheme  $\text{SanSig}$  is unlinkable, if for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{UnlinkabilityEx}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 6 returns 1 is negligibly close to  $\frac{1}{2}$  (as a function of  $\lambda$ ). The basic idea is that an adversary has to guess which message-signatures pair from the two inputs was chosen to be sanitized.*

For self-containment, we introduce the notation of the complete multi-sanitizer framework and refer to Canard et al. [13] for a complete discussion. We have a choose-then-guess adversary, which state is denoted as *st*. The algorithms and oracles are defined as follows:

- (1)  $\text{Setup}(1^\lambda, n, m)$  is the instance generator, where  $n$  denotes the amount of

*Experiment Pubaccountability*<sub>A</sub><sup>SanSig</sup>( $\lambda$ )

$(pk_{\text{sig}}, sk_{\text{sig}}) \leftarrow \text{KGen}_{\text{sig}}(1^\lambda)$   
 $(pk_{\text{san}}, sk_{\text{san}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $(pk^*, m^*, \sigma^*, \pi^*) \leftarrow \mathcal{A}_{\text{Sanit}(\dots, sk_{\text{san}})}^{\text{Sign}(sk_{\text{sig}}, \dots)}(pk_{\text{sig}}, pk_{\text{san}})$

Let  $(m_i, \text{ADM}_i, pk_{\text{san}, i})$  and  $\sigma_i$  for  $i = 1, 2, \dots, q$  be the queries to and from oracle **Sign**

return 1 if

$\forall i : (pk^*, m^*) \neq (pk_{\text{san}, i}, m_i)$ , and  
 $\text{Verify}(1^\lambda, m^*, \sigma^*, pk_{\text{sig}}, pk^*) = 1$ , and  
 $\text{Judge}(1^\lambda, m^*, \sigma^*, pk_{\text{sig}}, pk^*, \perp) = \text{Sig}$

Let  $(m_j, \text{MOD}_j, \sigma_j, pk_{\text{sig}, j})$  and  $(m'_j, \sigma'_j)$  be the queries to/from oracle **Sanit**

return 1 if:

$\forall j : (pk^*, m^*) \neq (pk_{\text{sig}, j}, m'_j)$ , and  
 $\text{Verify}(1^\lambda, m^*, \sigma^*, pk^*, pk_{\text{san}}) = 1$ , and  
 $\text{Judge}(1^\lambda, m^*, \sigma^*, pk^*, pk_{\text{san}}, \perp) = \text{San}$

return 0

**Fig. 7.** Non-Interactive Public Accountability

*Experiment Immutability*<sub>A</sub><sup>SanSig</sup>( $\lambda$ )

$(pk_{\text{sig}}, sk_{\text{sig}}) \leftarrow \text{KGen}_{\text{san}}(1^\lambda)$   
 $(pk_{\text{san}}^*, m^*, \sigma^*) \leftarrow \mathcal{A}_{\text{Sign}(sk_{\text{sig}}, \dots), \text{Proof}(sk_{\text{sig}}, \dots)}^{\text{Sanit}(sk_{\text{sig}}, \dots)}(pk_{\text{sig}})$

let  $(m_i, \text{ADM}_i, pk_{\text{san}, i})$  and  $\sigma_i$ ,  $i = 1, 2, \dots, q$  denote the queries to **Sign**

return 1, if:

$\text{Verify}(1^\lambda, m^*, \sigma^*, pk_{\text{sig}}, pk_{\text{san}}^*) = 1$ , and  
for all  $i = 1, 2, \dots, q$  we have:  
 $pk_{\text{san}}^* \neq pk_{\text{san}, i}$ , or  
 $m^*[j_i] \neq m_i[j_i]$ , where  $j_i \notin \text{ADM}_i$   
shorter messages are padded with  $\perp$

**Fig. 8.** Immutability

signers, while  $m$  denotes the number of sanitizers. Hence, PK contains all public keys, while SK contains all private keys. The adversary  $\mathcal{A}$  also gains access to sanitization, sign, proof and all “opening” oracles:

(2) **FindOri** returns the index of the original *signer*. If the message has been sanitized, **FindOri** returns 0, as “no signer exists”. It requires the opening key  $\text{osk}_{\text{ORI}}$ .

(3)  $\mathcal{CU}$  denotes the set of corrupted participants, i.e., all signers and sanitizers which secret key is known to the adversary. The adversary can gain access to the secret keys by using an implicit **Corrupt** oracle.

(4) **Judge** works as in our original definition, while it accounts for multiple signer, and sanitizers resp., and allows “partial” openings. In particular, it gets an additional parameter **ORI**. It outputs the index of the original signer, if the message has *not* been sanitized. See [13] for a complete discussion.

Our main observation is that it is crucial for the left-or-right oracle to check the validity of both signatures before proceeding. Else, the definition is not satisfiable and would not be satisfied by the scheme in [13]. The problem is that the left-or-right oracle receives two message-signature pairs and will sanitize one of them. If one of the signature is empty, then the sanitizing algorithm is unable to produce a valid signature because else, the sanitizer would be able to break immutability. Thus, if the adversary gives a valid message-signature pair to the oracle and a pair of a message and an empty (and thus invalid) signature, then in one case, the oracle returns  $\perp$ , and in the other case, the oracle returns a valid answer. Thus, the adversary can distinguish the two cases.

**Definition 6 (Non-Interactive Public Accountability).** *A sanitizable signature scheme  $\text{SanSig}$  is non-interactive public accountable, if for an empty proof  $\pi = \perp$ , and for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{Pubaccountability}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 7 returns 1 is negligible (as a function of  $\lambda$ ). The basic idea is that an adversary, i.e., the sanitizer or the signer, has to*

be able to make the *Judge* decide wrongly on an empty proof  $\pi = \perp$ . Note, *Proof* always returns  $\perp$  and therefore is not an oracle here.

**Definition 7 (Immutability).** A sanitizable signature scheme *SanSig* is immutable, if for any efficient algorithm  $\mathcal{A}$  the probability that the experiment  $\text{Immutability}_{\mathcal{A}}^{\text{SanSig}}(\lambda)$  given in Fig. 8 returns 1, is negligible (as a function of  $\lambda$ ). The basic idea is, that an adversary is not able to modify non-admissible blocks, even if it is able to choose the sanitizer key pair.

**Definition 8 (Secure SanSig).** We call a *SanSig* secure, if it is unlinkable, immutable and non-interactive publicly accountable.

Note, unlinkability implies privacy, while non-interactive public accountability implies accountability [11] and therefore also unforgeability [8]. Recall the following separation by *Brzuska* et al. [10], which also applies for our strengthened unlinkability definition, as the latter implies the original definition of unlinkability in [10], as we have already proven.

**Theorem 2 (Unlinkability  $\not\Rightarrow$  Transparency).** *There exists a scheme which is unlinkable, but not transparent.*

### 3 Efficient Perfectly Unlinkable SanSig

We introduce the building blocks used in the construction and then give a formal algorithmic description of our construction.

#### 3.1 Building Blocks

This section introduces the required building blocks for our construction. We require a deterministic signature scheme, unforgeable under chosen message attacks (UNF-CMA). Let  $\mathcal{DS} = (\text{DSKGen}, \text{DSSign}, \text{DSVerify})$  be such a signature scheme. Deterministic means, that signing identical messages leads to identical signatures, if signed with the same secret key  $sk$ . We want to emphasize that every unforgeable signature scheme can be transformed into a strongly unforgeable and also deterministic scheme using several transformations [6, 20]. An example for a standardized deterministic signature scheme is “RSASSA-PKCS-v1.5-SIGN” [26].

#### 3.2 Algorithmic Description

Our scheme is inspired by the constructions given in [9] and [11]. It achieves unforgeability, immutability, non-interactive public accountability, perfect privacy, perfect unlinkability and sanitizer- and signer-accountability. Therefore, it meets all legal and the essential cryptographic requirements.

**Construction 1 (Secure SanSig)** *Let  $\mathcal{DS} = (\text{DSKGen}, \text{DSSign}, \text{DSVerify})$  be a deterministic and unforgeable signature scheme. Define the sanitizable signature scheme  $\text{SanSig} = (\text{KGen}_{\text{sig}}, \text{KGen}_{\text{san}}, \text{Sign}, \text{Sanit}, \text{Verify}, \text{Judge})$  as follows:*

**Key Generation:** Algorithm  $KGen_{sig}$  generates on input of the security parameter  $\lambda$  a key pair  $(pk_{sig}, sk_{sig}) \leftarrow DSKGen(1^\lambda)$  of the underlying signature scheme  $\mathcal{DS}$ , and algorithm  $KGen_{san}$  for input  $\lambda$  analogously returns a pair  $(pk_{san}, sk_{san}) \leftarrow DSKGen(1^\lambda)$ .

**Signing:** Algorithm  $Sign$  on input  $m \in \{0, 1\}^*$ ,  $sk_{sig}$ ,  $pk_{san}$ ,  $ADM$  and computes

$$\sigma_{FIX} \leftarrow DSSign(sk_{sig}, (0, m[FIX], ADM, pk_{san})),$$

$$\sigma_{FULL} \leftarrow DSSign(sk_{sig}, (1, m, pk_{san}, pk_{sig}))$$

using the underlying signing algorithm. It returns:

$$(m, \sigma) = (m, (\sigma_{FIX}, \sigma_{FULL}, ADM))$$

**Sanitizing:** Algorithm  $Sanit$  on input of message  $m$ , (maybe empty) modification instructions  $MOD$ , a signature  $\sigma = (\sigma_{FIX}, \sigma_{FULL}, ADM)$ , keys  $pk_{sig}$  and  $sk_{san}$ , first checks that  $MOD$  is admissible according to  $ADM$  and that  $\sigma_{FIX}$  is a valid signature for message  $(0, m[FIX], ADM, pk_{san})$  under key  $pk_{sig}$ . If not, it stops and outputs  $\perp$ . Else, it generates the modified message  $m' \leftarrow MOD(m)$  and computes

$$\sigma'_{FULL} \leftarrow DSSign(sk_{san}, (1, m', pk_{san}, pk_{sig}))$$

and outputs  $(m', \sigma') = (m', (\sigma_{FIX}, \sigma'_{FULL}, ADM))$ .

**Verification:** Algorithm  $Verify$  on input of a message  $m \in \{0, 1\}^*$ , a signature  $\sigma = (\sigma_{FIX}, \sigma_{FULL}, ADM)$  and public keys  $pk_{sig}$ ,  $pk_{san}$  first checks that  $\sigma_{FIX}$  is a valid signature for message  $(0, m[FIX], ADM, pk_{san})$  under key  $pk_{sig}$  by checking that  $DSVerify(pk_{sig}, (0, m[FIX], ADM, pk_{san}), \sigma_{FIX}) = 1$ . Second, it returns 1, if:  $DSVerify(pk_{sig}, (1, m, pk_{san}, pk_{sig}), \sigma_{FULL}) = 1$  or  $DSVerify(pk_{san}, (1, m, pk_{san}, pk_{sig}), \sigma_{FULL}) = 1$ . This declares the entire signature as valid. Otherwise it returns 0.

**Proof:** The  $Proof$  algorithm always returns  $\perp$

**Judge:** Judge on input of  $m, \sigma, pk_{sig}, pk_{san}$  and  $\perp$  parses  $\sigma$  as  $(\sigma_{FIX}, \sigma_{FULL}, ADM)$  and outputs  $Sig$ , if:

$$DSVerify(pk_{sig}, (1, m, pk_{san}, pk_{sig}), \sigma_{FULL}) = 1$$

It returns  $San$ , if:

$$DSVerify(pk_{san}, (1, m, pk_{san}, pk_{sig}), \sigma_{FULL}) = 1$$

If none verifies, it returns  $\perp$ .

**Theorem 3 (Our construction is secure.)** *If the underlying signature scheme  $DS$  is UNF-CMA and deterministic, then our construction is immutable, perfectly unlinkable, perfectly private, non-interactive publicly accountable (and therefore signer-/sanitizer accountable and also unforgeable [8, 11]), i.e., secure.*

The proof is delegated to Appendix A.

## 4 Extensions: Multiple Sanitizers & Selective Linkability

We deploy a deterministic, strongly unforgeable signature scheme to obtain unlinkability. In the following, we show that by replacing the signature scheme for the fixed blocks with certain other types of signature schemes, one obtains interesting additional features, which have not been considered yet. In this section, we extend our scheme to cope with multiple sanitizers and allow for more fine-grained control.

**Multiple Sanitizer & Speed-Up.** Our construction can be modified to work in the multi-sanitizer framework [13]. In particular, the signer can add a public key  $pk_{\text{san},i}$  for each sanitizer  $i$ . Our simple yet effective alteration once again demonstrates the generality of the underlying basic idea and its broad applicability. Additionally, all mentioned modifications impact the performance of the scheme only lightly, as they require only a constant number of additional steps per sanitizer. To improve the speed of the multi-sanitizer verification procedure, one can append a hint on the required public key to the signature. This small improvement allows skipping the need to iterate through all public keys in  $\sigma_{\text{FIX}}$ . This also holds when considering only one sanitizer and one signer. For a meaningful definition of unlinkability in the multi-sanitizer case, we require that only one sanitizer acts as the sanitizer in the unlinkability experiment, while we also require that the sanitizers are fixed. The latter is in conjunction with [13]. To enhance anonymity for the sanitizers, one can also use a group signature scheme for the *sanitizers*. As the original signer still uses a normal signature scheme, the signatures are clearly distinguishable and therefore remain legally recognized, following the reasoning of [34]. In certain scenarios, the weakened unlinkability definition still suffices, if it is obvious in the practical application which entity has generated the signature.

**Signer Selected Linkability by Strongly Unforgeable Signatures.** A strongly unforgeable signature scheme is an unforgeable signature scheme, where, additionally, it is hard to generate new signatures for previously signed messages [2]. If the signature generation of a strongly unforgeable scheme is randomized, then signatures for a message are not unique which harms unlinkability in our construction. Thus, if we de-randomize the linkable scheme by using a  $\mathcal{PRF}$  [20] to generate the randomness for the signing algorithm deterministically from the input message, then the signer is able to make that signature unlinkable. In detail, we consider the  $\mathcal{PRF}$ -key as part of  $sk_{\text{sig}}$ . Then, if two signatures are designated to be unlinkable, the used randomness is deterministically generated by applying the  $\mathcal{PRF}$  on a digest of the fixed part of the message that is generated using a collision-resistant hash function. On the other hand, if the used randomness is not generated using the  $\mathcal{PRF}$ , the resulting sanitized documents can be linked. Overall, the  $\mathcal{PRF}$ -de-randomized scheme allows the signer to decide whether signed messages shall be linkable or unlinkable. It remains to establish formally that these properties hold.

		KeyGen			Sign			Sanit of 25% of $\ell$			Verify			Detect		
$\lambda$	$\ell$	100/1k/10k			100	1k	10k	100	1k	10k	100	1k	10k	100	1k	10k
	2.048 Bit		1,934			22	24	26	13	14	17	1	1	4	1	2
4.096 Bit		16,280			149	150	149	78	79	84	4	4	8	5	5	9

**Table 1.** Median runtime of our scheme;  $\ell$  is the number of blocks; All in ms

**Sanitizer Selective Linkability by Randomizable Signatures.** As already proposed by *Brzuska et al.*, re-randomizable signatures are also suitable to achieve unlinkability [10]. Interestingly, here, a dual observation to the  $\mathcal{PRF}$ -case applies. Namely, the sanitizer gets to choose whether a sanitized message shall be linkable to the original one or not. Note, this feature comes with the caveat that the signer relies on good randomness added by the sanitizer. If the sanitizing process is carried out by a weak or only partially trusted device, one might prefer to opt against re-randomizable signatures and use deterministic ones, as proposed in our construction. On the other hand, it allows the signer to delegate the decision to enable linkability for certain messages to the sanitizer.

## 5 Performance Measurements

To demonstrate practical usability, we implemented our construction. All tests were performed on an *Intel T8300 Dual Core @2.40 GHz* and 4 GiB of RAM, running *Ubuntu Version 12.04 LTS (64 Bit)* and Java version 1.7.0\_03. For all tests, we applied our algorithms to messages with 100, 1,000 (1k) and 10,000 (10k) blocks. For any block count, we decided to fix the amount of admissible blocks to 50%, and we sanitized always 50% of the admissible blocks, i.e., 25% of all blocks. We took the median of 100 runs. We used one possible choice for a deterministic signature scheme, namely “RSASSA-PKCS-v1\_5-SIGN” [26]. We utilized a single thread to calculate the signatures. Obviously, parallelization, e.g., by using CRT, will yield significant performance improvements. The results of our measurements in Tab. 1 show that our scheme keeps a very high performance. The source code is available upon request.

## References

1. J. H. Ahn, D. Boneh, J. Camenisch, S. Hohenberger, A. Shelat, and B. Waters. Computing on authenticated data. ePrint Report 2011/096, 2011.
2. J. H. An, Y. Dodis, and T. Rabin. On the security of joint signature and encryption. In *EUROCRYPT*, pages 83–107, 2002.
3. G. Ateniese, D. H. Chou, B. de Medeiros, and G. Tsudik. Sanitizable signatures. In *ESORICS*, pages 159–177. Springer-Verlag, 2005.
4. N. Attrapadung, B. Libert, and T. Peters. Computing on authenticated data: New privacy definitions and constructions. In *ASIACRYPT*, pages 367–385, 2012.

5. N. Attrapadung, B. Libert, and T. Peters. Efficient completely context-hiding quotable and linearly homomorphic signatures. In *PKC*, pages 386–404, 2013.
6. M. Bellare and S. Shoup. Two-tier signatures, strongly unforgeable signatures, and fiat-shamir without random oracles. In *PKC*, pages 201–216, 2007.
7. C. Brzuska, H. Busch, O. Dagdelen, M. Fischlin, M. Franz, S. Katzenbeisser, M. Mantulis, C. Onete, A. Peter, B. Poettering, and D. Schröder. Redactable Signatures for Tree-Structured Data: Definitions and Constructions. *ACNS'10*, pages 87–104. Springer, 2010.
8. C. Brzuska, M. Fischlin, T. Freudenreich, A. Lehmann, M. Page, J. Schelbert, D. Schröder, and F. Volk. Security of Sanitizable Signatures Revisited. In *Proc. of PKC 2009*, pages 317–336. Springer, 2009.
9. C. Brzuska, M. Fischlin, A. Lehmann, and D. Schröder. Sanitizable signatures: How to partially delegate control for authenticated data. In *Proc. of BIOSIG*, volume 155 of *LNI*, pages 117–128. GI, 2009.
10. C. Brzuska, M. Fischlin, A. Lehmann, and D. Schröder. Unlinkability of Sanitizable Signatures. In *Public Key Cryptography*, pages 444–461, 2010.
11. C. Brzuska, H. C. Pöhls, and K. Samelin. Non-Interactive Public Accountability for Sanitizable Signatures. In *EuroPKI*, volume 7868 of *LNCS*, pages 178–193. Springer-Verlag, 2012.
12. S. Canard and A. Jambert. On extended sanitizable signature schemes. In *CT-RSA*, pages 179–194, 2010.
13. S. Canard, A. Jambert, and R. Lescuyer. Sanitizable signatures with several signers and sanitizers. In *AFRICACRYPT*, pages 35–52, 2012.
14. R. Canetti, S. Halevi, and J. Katz. A forward-secure public-key encryption scheme. In *EUROCRYPT*, pages 255–271, 2003.
15. R. M. Caplan. HIPAA. Health Insurance Portability and Accountability Act of 1996. *Dent Assist*, 72(2):6–8, 1997.
16. E.-C. Chang, C. L. Lim, and J. Xu. Short Redactable Signatures Using Random Trees. *CT-RSA '09*, pages 133–147, Berlin, Heidelberg, 2009. Springer-Verlag.
17. D. Chaum and E. van Heyst. Group signatures. In *EUROCRYPT*, pages 257–265, 1991.
18. H. de Meer, H. C. Pöhls, J. Posegga, and K. Samelin. Scope of security properties of sanitizable signatures revisited. In *ARES*, pages 188–197, 2013.
19. B. Deiseroth, V. Fehr, M. Fischlin, M. Maasz, N. F. Reimers, and R. Stein. Computing on authenticated data for adjustable predicates. In *ACNS*. Springer, 2013.
20. O. Goldreich. Two remarks concerning the goldwasser-micali-rivest signature scheme. In *CRYPTO*, pages 104–110, 1986.
21. J. Gong, H. Qian, and Y. Zhou. Fully-secure and practical sanitizable signatures. In *InsCrypt*, volume 6584 of *LNCS*, pages 300–317. Springer, 2011.
22. S. Haber, Y. Hatano, Y. Honda, W. G. Horne, K. Miyazaki, T. Sander, S. Tezoku, and D. Yao. Efficient signature schemes supporting redaction, pseudonymization, and data deidentification. In *ASIACCS*, pages 353–362, 2008.
23. C. Hanser and D. Slamanig. Blank digital signatures. In *AsiaCCS*, pages 95 – 106. ACM, 2013.
24. T. Izu, N. Kunihiro, K. Ohta, M. Sano, and M. Takenaka. Information security applications. In *ISC*, chapter Sanitizable and Deletable Signature, pages 130–144. Springer-Verlag, Berlin, Heidelberg, 2009.
25. R. Johnson, D. Molnar, D. Song, and D. Wagner. Homomorphic signature schemes. pages 244–262. Springer, Feb. 2002.
26. J. Jonsson and B. Kaliski. Public-Key Cryptography Standards (PKCS) #1: RSA Cryptography Specifications Version 2.1. RFC 3447 (Informational), 2 2003.

27. M. Klonowski and A. Lauks. Extended Sanitizable Signatures. In *ICISC*, pages 343–355, 2006.
28. H. Krawczyk and T. Rabin. Chameleon Hashing and Signatures. In *Symposium on Network and Distributed Systems Security*, pages 143–154, 2000.
29. A. Kundu and E. Bertino. How to authenticate graphs without leaking. In *EDBT*, pages 609–620, 2010.
30. J. Lai, X. Ding, and Y. Wu. Accountable trapdoor sanitizable signatures. In *ISPEC*, pages 117–131, 2013.
31. M. Mambo and E. Usuda, K. and Okamoto. Proxy signatures for delegating signing operation. CCS '96, pages 48–57, New York, NY, USA, 1996. ACM.
32. K. Miyazaki, G. Hanaoka, and H. Imai. Digitally signed document sanitizing scheme based on bilinear maps. ASIACCS '06, pages 343–354. ACM, 2006.
33. K. Miyazaki, M. Iwamura, T. Matsumoto, R. Sasaki, H. Yoshiura, S. Tezuka, and H. Imai. Digitally Signed Document Sanitizing Scheme with Disclosure Condition Control. *IEICE Transactions*, 88-A(1):239–246, 2005.
34. H. C. Pöhls and F. Höhne. The role of data integrity in eu digital signature legislation - achieving statutory trust for sanitizable signature schemes. In *STM. LNCS*, 2011.
35. H. C. Pöhls, S. Peters, K. Samelin, J. Posegga, and H. de Meer. Malleable signatures for resource constrained platforms. In *WISTP*, pages 18–33, 2013.
36. H. C. Pöhls, K. Samelin, and J. Posegga. Sanitizable Signatures in XML Signature - Performance, Mixing Properties, and Revisiting the Property of Transparency. In *ACNS*, volume 6715 of *LNCS*, pages 166–182. Springer-Verlag, 2011.
37. K. Samelin, H. C. Pöhls, A. Bilzhause, J. Posegga, and H. de Meer. On Structural Signatures for Tree Data Structures. In *ACNS*, volume 7341 of *LNCS*, pages 171–187. Springer-Verlag, 2012.
38. K. Samelin, H. C. Pöhls, A. Bilzhause, J. Posegga, and H. de Meer. Redactable signatures for independent removal of structure and content. In *ISPEC*, volume 7232 of *LNCS*, pages 17–33. Springer-Verlag, 2012.
39. R. S. Sandhu, E. J. Coyne, H. L. Feinstein, and C. E. Youman. Role-based access control models. *Computer*, 29(2):38–47, February 1996.
40. R. Steinfeld and L. Bull. Content extraction signatures. Springer, 2002.
41. D. H. Yum and P. J. Lee. Sanitizable signatures reconsidered. *IEICE Transactions*, 94-A(2):717–724, 2011.
42. D. H. Yum, J. W. Seo, and P. J. Lee. Trapdoor sanitizable signatures made easy. ACNS'10, pages 53–68, Berlin, Heidelberg, 2010. Springer-Verlag.

## A Security of Our Construction

The security proofs of our construction follow the ideas of [9] and [11]. From [8, 9, 11] we yield that non-interactive public accountability, as defined in [11], already implies sanitizer accountability, signer accountability and unforgeability. Moreover, unlinkability implies privacy [9]. Thus, it suffices to prove that Construction 1 is immutable, non-interactive publicly accountable and unlinkable.

*Proof (of Th. 3).* To increase the readability, we prove each property on its own.

- *Unlinkability.* For two messages  $m^0$  and  $m^1$  with identical fixed parts  $m[\text{FIX}]$ , the signatures  $\sigma_{\text{FIX}}^0$  and  $\sigma_{\text{FIX}}^1$  over this part are identical, as we use a deterministic signature scheme. Moreover, the signatures  $\sigma_{\text{FULL}}^0$  and  $\sigma_{\text{FULL}}^1$ , depending

on the modifiable message parts, are not used as input for the sanitizing process. Thus, we are perfectly unlinkable and perfectly private.

- *Immutability.* Assume towards contradiction that Construction 1 is not immutable. In particular, let  $\mathcal{A}$  be an efficient adversary against immutability. We construct an adversary  $\mathcal{B}$  against the underlying signature scheme. The adversary  $\mathcal{B}$  embeds the keys of the signature scheme as the signer’s public keys. It then answers  $\mathcal{A}$ ’s queries to the signing oracle by running the algorithm as described in Construction 1, except for signature generation under the signer’s key, where  $\mathcal{B}$  queries its signing oracle instead of computing them itself. The simulation is perfect. When  $\mathcal{A}$  returns  $(m^*, pk_{\text{san}}^*, \sigma^*)$ , then  $\mathcal{B}$  returns  $((0, m[\text{FIX}], \text{ADM}, pk_{\text{san}}^*), \sigma_{\text{FIX}})$  as a forgery. We now prove that  $\mathcal{B}$  is successful in attacking the underlying signature scheme, if  $\mathcal{A}$  is.

Following our definition,  $\mathcal{A}$  wins, if it can output a tuple  $(m^*, \sigma^*, pk_{\text{san}}^*)$  such that  $\text{Verify}(m^*, \sigma^*, pk_{\text{sig}}^*, pk_{\text{san}}^*) = 1$  and  $pk_{\text{san}}^* \neq pk_{\text{san},i}^*$  for all  $i$  queries to the signing oracle or  $\exists i, j, j_i \notin \text{ADM} : m^*[j_i] \neq m_i[j_i]$ .

- (i) If  $pk_{\text{san}}^* \neq pk_{\text{san},i}^*$ , then  $(0, *, *, pk_{\text{san}}^*)$  is fresh.
  - (ii) If  $\exists i, j, j_i \notin \text{ADM} : m^*[j_i] \neq m_i[j_i]$ , then  $(0, m[\text{FIX}]^*, \text{ADM}, pk_{\text{san}}^*)$  is fresh.
- These cases are equal to the attack cases for forgeries of the underlying signature scheme. Thus,  $\mathcal{B}$ ’s success probability is equal to  $\mathcal{A}$ ’s success probability.

- *Non-Interactive Public Accountability.* Let  $\mathcal{A}$  be an efficient adversary against non-interactive public accountability. We construct another efficient adversary  $\mathcal{B}$  against the unforgeability of the underlying signature scheme  $\mathcal{DS}$  as follows.  $\mathcal{B}$  gets as input a public key  $pk$  and flips a coin  $b$ . If  $b = 0$ , it sets  $pk_{\text{sig}} := pk$  and runs  $\text{DSKGen}$  to generate  $(pk_{\text{san}}, sk_{\text{san}})$ . If  $b = 1$ , it sets  $pk_{\text{san}} := pk$  and runs  $\text{DSKGen}$  to generate  $(pk_{\text{sig}}, sk_{\text{sig}})$ . To simulate the oracles for  $\mathcal{A}$ , the algorithm  $\mathcal{B}$  runs the algorithms  $\text{Sign}$  and  $\text{Sanit}$  according to the specification with the exception that whenever a signature is generated under the secret key  $sk$  corresponding to  $pk$ ,  $\mathcal{B}$  does not generate the signature itself. Instead,  $\mathcal{B}$  queries its signing oracle and passes the result to  $\mathcal{A}$ . Eventually, the adversary  $\mathcal{A}$  outputs a triple  $(pk^*, m^*, \sigma^*)$ . We distinguish between two cases, a malicious sanitizer attack and a malicious signer attack. With probability  $\frac{1}{2}$  the simulation was done for the correct case, as in both cases, the output distributions of  $\mathcal{B}$ ’s simulation are identical.

*Malicious Sanitizer*

$\mathcal{B}$  returns  $((0, m[\text{FIX}]^*, \text{ADM}, pk_{\text{san}}^*), \sigma_{\text{FIX}})$ . As  $m[\text{FIX}]^*$  is fresh, the signing oracle has never signed a message of the form  $(0, m[\text{FIX}], \text{ADM}, *)$ .

*Malicious Signer*

$\mathcal{B}$  returns  $((1, m^*, pk_{\text{san}}^*, pk_{\text{sig}}^*), \sigma_{\text{FULL}})$ . As  $m^*$  is fresh, the signing oracle has never signed a message of the form  $(1, m^*, *, *)$ .

*Analysis*

Thus, the overall success probability of  $\mathcal{B}$  is exactly  $\frac{1}{2}$  the success probability of  $\mathcal{A}$ .

□