

Structure-Preserving Signatures on Equivalence Classes From Standard Assumptions

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Abstract. Structure-preserving signatures on equivalence classes (SPS-EQ) introduced at ASIACRYPT 2014 are a variant of SPS where a message is considered as a projective equivalence class, and a new representative of the same class can be obtained by multiplying a vector by a scalar. Given a message and corresponding signature, anyone can produce an updated and randomized signature on an arbitrary representative from the same equivalence class. SPS-EQ have proven to be a very versatile building block for many cryptographic applications.

In this paper, we present the first EUF-CMA secure SPS-EQ scheme under standard assumptions. So far only constructions in the generic group model are known. One recent candidate under standard assumptions are the weakly secure equivalence class signatures by Fuchsbauer and Gay (PKC'18), a variant of SPS-EQ satisfying only a weaker unforgeability and adaption notion. Fuchsbauer and Gay show that this weaker unforgeability notion is sufficient for many known applications of SPS-EQ. Unfortunately, the weaker adaption notion is only proper for a semi-honest (passive) model and as we show in this paper, makes their scheme unusable in the current models for almost all of their advertised applications of SPS-EQ from the literature.

We then present a new EUF-CMA secure SPS-EQ scheme with a tight security reduction under the SXDH assumption providing the notion of perfect adaption (under malicious keys). To achieve the strongest notion of perfect adaption under malicious keys, we require a common reference string (CRS), which seems inherent for constructions under standard assumptions. However, for most known applications of SPS-EQ we do not require a trusted CRS (as the CRS can be generated by the signer during key generation). Technically, our construction is inspired by a recent work of Gay et al. (EUROCRYPT'18), who construct a tightly secure message authentication code and translate it to an SPS scheme adapting techniques due to Bellare and Goldwasser (CRYPTO'89).

1 Introduction

Structure-preserving signatures (SPS) [4] are signatures where the messages, public keys and signatures only consists of elements of groups equipped with an

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efficient bilinear map, and the verification algorithm just consists of group membership checks and evaluation of pairing product equations (PPEs). SPS schemes [4, 5, 2, 6, 64, 44, 63, 45, 7, 60, 43, 8] are compatible with efficient pairing-based NIZK proofs [50], and are a useful building-block for many cryptographic applications, such as blind signatures [4, 39], group signatures [4, 68], traceable signatures [3], group encryption [23], homomorphic signatures [66], delegatable anonymous credentials [34], compact verifiable shuffles [24], network coding [10], oblivious transfer [48], tightly secure encryption [56] and anonymous e-cash [17]. SPS schemes come in various different flavors such as being able to sign elements in either one or both source groups of the bilinear group or requiring certain conditions for messages (e.g., messages need to be Diffie-Hellman tuples [33, 45]). They come with different provable security guarantees, ranging from ones that are directly analyzed in the generic group model (GGM) to ones that can be constructed from standard assumptions such as SXDH or SXDLin (typically within the Matrix-Diffie-Hellman assumption framework [31]) and under different qualities of the reduction (from very loose to tight reductions). A desirable goal is to construct schemes with tight security reductions from standard assumptions which are at the same time highly efficient. Some SPS schemes are also randomizable (e.g., [4, 6]), meaning that a signature can be randomized to another unlinkable valid signature on the same message.

Structure-preserving signatures on equivalence classes (SPS-EQ) [52, 38, 40] are a variant of SPS where anyone can randomize not only signatures, but a message-signature pair publicly, i.e., in addition to randomizing the signature also the message can be randomized. They have proven to be useful in many applications such as attribute-based anonymous credentials [52, 29, 40], delegatable anonymous credentials [27], self-blindable certificates [11], blind signatures [39, 37], group signatures [30, 11, 26, 12], sanitizable signatures [22], verifiably encrypted signatures [51], access control encryption [36] or proving the correctness of a shuffle in mix-nets (i.e., for anonymous communication or electronic voting) [59]. In many of these applications, the idea of randomizing signatures and messages offers the same functionality as when using SPS schemes combined with a NIZK proof, but without the need for any NIZK. Consequently, this allows for the design of more efficient constructions.

More concretely, in an SPS-EQ scheme, given a signature on an equivalence class defined over the message space, anyone can update the signature to another representative of the same class. Defined on $(\mathbb{G}^*)^\ell$ (where \mathbb{G} is of prime order p), this equivalence relation $\sim_{\mathcal{R}}$ is as follows ($\ell > 1$):

$$\mathbf{M} \in (\mathbb{G}^*)^\ell \sim_{\mathcal{R}} \mathbf{N} \in (\mathbb{G}^*)^\ell \Leftrightarrow \exists \mu \in \mathbb{Z}_p^* : \mathbf{M} = \mu \mathbf{N}$$

An SPS-EQ scheme signs an equivalence class $[\mathbf{M}]_{\mathcal{R}}$ for $\mathbf{M} \in (\mathbb{G}_i^*)^\ell$ by signing a representative \mathbf{M} of $[\mathbf{M}]_{\mathcal{R}}$. It then allows for switching to other representatives of $[\mathbf{M}]_{\mathcal{R}}$ and updating the signature without access to the secret key. Two important properties of SPS-EQ are *unforgeability* (EUFCMA security) defined on equivalence classes and *perfect adaption* (potentially even under malicious signing keys), where the latter requires that updated signatures (output by the

algorithm `ChgRep`) are distributed identically to new signatures on the respective representative (if signatures or even if signing keys are computed maliciously). Latter together with the DDH assumption on the message space then yields a notion of unlinkability, i.e., that original signatures and those output by `ChgRep` cannot be linked. As it turns out, coming up with constructions that achieve *both notions simultaneously* is a challenging task.

We note that, as observed in [39], every SPS-EQ yields a (randomizable) SPS scheme by appending some fixed group element to the message vector before signing and which is checked on verification, to allow only one single representative of each class. Recently, the concept of SPS-EQ has even been further extended to consider also equivalence classes on the public keys, denoted as signatures with flexible public key [11] and equivalence classes on messages and public keys simultaneously, denoted as mercurial signatures [27]. This further extends the scope of applications.

Prior approaches to construct SPS-EQ. The first instantiation of SPS-EQ in [52] was secure only against random message attacks, and later Fuchsbauer et al. [38, 40] presented a revised scheme that achieves EUF-CMA security in the generic group model (GGM). In [39], Fuchsbauer et al. present another EUF-CMA secure scheme under a q -type assumption, which by construction does not provide the perfect adaption notion and thus is not interesting for existing applications of SPS-EQ. Recently, Fuchsbauer and Gay [35], presented a version of SPS-EQ (called equivalence class signatures or EQS) which can be proven secure under standard assumptions, i.e., in the Matrix-Diffie-Hellman assumption framework [31]. In order to prove their scheme secure, they have introduced a weakened unforgeability notion called existential unforgeability under chosen open message attacks (EUF-CoMA), in which the adversary does not send group element vectors to the signing oracle but vectors of \mathbb{Z}_p^* elements. Moreover, in contrast to the original definition of SPS-EQ in [52] and the scheme of Fuchsbauer et al. [38, 40], which allows to randomize a given signature (change the representative) an arbitrary number of times, the scheme of Fuchsbauer and Gay [35] distinguishes two types of signatures. The first type comes from the signing algorithm and when randomized yields a signature of the second type, which cannot be randomized any further. As argued by Fuchsbauer and Gay in [35], for most of the known applications of SPS-EQ the combination of EUF-CoMA notion and the one-time randomizability is sufficient. Actually, as argued in [35], it is sufficient for all applications in the literature, except for the one to round-optimal blind signatures from SPS-EQ [39].

The construction of Fuchsbauer and Gay in [35] does also rely on a weakened notion of adaption (weaker than the original one from [39] in that it only considers honestly generated keys and honestly computed signatures). We will show that even though their weaker unforgeability notion is sufficient for applications, the weaker adaption notion makes the scheme suitable only for restricted applications, i.e., access control encryption (ACE) or attribute-based credentials (ABCs) with an honest credential issuer. Moreover, the application to verifiably encrypted signatures in [51] requires another notion called perfect composition,

which [35] seem to assume implicitly. Unfortunately, their scheme does not satisfy this notion. Consequently, for the interesting schemes providing the perfect adaption notion from [39], the current state of affairs is that there is only the EUF-CMA secure scheme from [38, 40] secure in the GGM.

Tight security for SPS-EQ schemes. Tight security allows to choose cryptographic parameters of a scheme in a way that is supported by a security proof, without the need to sacrifice efficiency by compensating the security loss of a reduction with larger parameters. Latter can be significant if the reduction is very loose. In case of SPS, quite some progress has been made in recent years on constructing tightly-secure SPS [55, 7, 60, 8, 43], though the state-of-the-art tightly-secure schemes under standard assumptions are still less efficient than for instance schemes proven secure in the generic group model (GGM). While tight security is quite well studied within SPS (and other primitives such as encryption [55, 41, 54], signatures [55, 25, 54, 46], identity-based encryption [25, 58, 57], key exchange [13, 46, 53], or zero-knowledge proofs [55, 41]), there are no such results for SPS-EQ schemes so far.

1.1 Our Contributions

Our contributions in this paper can be summarized as follows:

Analysis of FG18: Firstly, we revisit the concrete approach to construct EUF-CoMA secure EQS from Fuchsbauer and Gay in [35], representing the only known candidate towards perfectly adapting SPS-EQ under standard assumptions so far. Thereby, we identify various problems with the applications of the scheme presented in [35]. We stress that we do not present attacks on the scheme itself (which is secure in their model), but show that their adaption notion is too weak for most applications claimed in [35] (apart from access control encryption (ACE) [36]). Briefly summarizing, we first show that their scheme cannot be used for the application to attribute-based credentials (ABCs) [38, 40]. We demonstrate an attack based on a trapdoor in the signing key that invalidates the anonymity proof for ABCs. Secondly, we show an attack that demonstrates that the scheme in [35] cannot be used even for applications that assume honest generation of signing keys and in particular for ABCs under honest-keys [52] and dynamic group signatures [30]. We stress that due to this too weak adaption notion concrete instantiations presented in follow up works by Backes et al. [11, 12], that rely on the FG18 scheme from [35], are invalidated and need to be reconsidered. Our results allow to repair their now broken claims in part.³ Thirdly, we show that the FG18 scheme does not satisfy another notion called perfect composition [51], invalidating the use of their scheme for application to verifiably encrypted signatures as discussed in [35]. Consequently, this means that contrary to their claim, the EQS framework and scheme in [35] can only be used for the construction of access control encryption (ACE) in [36] and for

³ For the group signatures in [12] it will only work with our construction when relying on a CRS, or by using the construction secure in the GGM in [38].

all other applications no instantiations under standard assumptions remain. We stress that one could relax the security models of the applications to make [35] usable again, but such models where signatures and keys are assumed to be generated honestly, i.e., that only guarantee semi-honest (passive) security, limits the practical applications. For example, one could consider ABCs with anonymity against honest credential issuers and use the EQS from [35].

SPS-EQ from standard assumptions and applications: As our main contribution, we provide the first construction of SPS-EQ under standard assumptions and in particular the Matrix-Diffie-Hellman assumption framework. We therefore have to revise the model of SPS-EQ in some aspects: (1) we introduce tags, where the signing algorithm outputs a signature and a tag, randomization (i.e., ChgRep) requires a signature and a tag, whereas for verification only the signature is required; signatures that have been randomized using a tag can not further be randomized, i.e., only a single randomization is possible. This definition is comparable to the one in [35], apart that FG18 does not use tags. We stress that as demonstrated in [35], this restriction does not affect existing applications of SPS-EQ. (2) we require that signers generate their signing keys with respect to a common reference string (CRS) for achieving the perfect adaption notion in the malicious setting (prior works on SPS-EQ did not consider having a CRS). We will show that this does not impact the applications discussed in [35] with the exception of anonymous credentials in the malicious key model, as the security models in all other applications assume honest generation of the signing keys and thus every signer can produce its own CRS as part of the signing key. As we, however, cannot avoid a CRS in the malicious key setting, we are not able to instantiate round-optimal blind signatures in the standard model from SPS-EQ [39] under standard assumptions, which [35] could not achieve either. On the positive side, however, it allows us to obtain the most efficient round-optimal blind signatures in the CRS model from standard assumptions.

On the use of a CRS. Although our scheme does not require a CRS for nearly all of the applications of SPS-EQ, avoiding a CRS in the malicious setting would be good. The use of a CRS in general seems to be debatable, as it needs to be generated by some trusted third party that is hard to find in the real world. Within recent years, we have seen a number of deployed real-world applications that require a CRS when using zk-SNARKS (e.g., Zcash⁴ being probably the most prominent one) and which have used multi-party computation ceremonies to construct the CRS in a way that no entity provably knows the trapdoor. A number of such ceremonies has been run in real-world⁵ and various works discuss approaches to achieve it [16, 21, 20]. In the light of this, we do not consider it unrealistic to generate a CRS for the use within practical applications of SPS-EQ that require security under malicious keys, especially since the CRS does not depend on the message length ℓ and so a single CRS can be used for

⁴ <https://z.cash/>

⁵ see e.g., <https://z.cash/blog/the-design-of-the-ceremony/> or <https://www.zfnd.org/blog/conclusion-of-powers-of-tau/>.

all types of SPS-EQ keys for different applications. Furthermore, it seems interesting to investigate the application of recent approaches towards subversion resistant (QA)-NIZK [14, 1] or updatable CRS [49, 69], though this typically comes at the cost of rather strong knowledge assumptions. Clearly, ultimately it would be good to find SPS-EQ in the malicious key model without a CRS, which we leave as a challenging open problem.

1.2 Outline of our Construction

Fuchsbauer and Gay [35] modify an affine MAC of Blazy et al. [18] to obtain a linear structure-preserving MAC. Then, they make the scheme publicly verifiable using a known technique from Kiltz and Wee [65] already used previously in context of SPS [64]. Unfortunately, the structure-preserving MAC has an inherent problem in the security game, where both messages and Matrix Decision Diffie-Hellman (MDDH) challenges belong to the same source group of the bilinear group. This forces them to use the weaker EUF-CoMA instead of EUF-CMA security. Consequently, as we are interested in EUF-CMA security, we need to look for a different framework when trying to construct EUF-CMA secure SPS-EQ schemes.

Therefore, we borrow a central idea from the recent work of Gay et al. [43]. In particular, they use a specific OR-proof [71] to then construct tightly secure structure-preserving MACs based on the key encapsulation mechanism of Gay et al. in [42]. More precisely, they make use of adaptive partitioning [54] to randomize all tags in their MAC. Their work is based on the observation (core lemma in [43]) that for all $[\mathbf{t}]_1 = [\mathbf{A}_0]_1 \mathbf{r}$ with $\mathbf{r} \xleftarrow{R} \mathbb{Z}_p^k$ chosen freshly for each instance, fixed matrices $\mathbf{A}_0, \mathbf{A}_1 \xleftarrow{R} \mathcal{D}_{2k,k}$, and a NIZK proof π for $\mathbf{t} \in \text{span}(\mathbf{A}_0) \cup \text{span}(\mathbf{A}_1)$, the following values

$$\mathbf{k}_0^\top [\mathbf{t}]_1, \quad (\mathbf{k}_0^\top + \mathbf{s}^\top) [\mathbf{t}]_1 \quad (1)$$

are indistinguishable under the MDDH assumption, where $\mathbf{k}_0 \leftarrow \mathbb{Z}_p^{2k}$ is a key, and $\mathbf{s} \in \mathbb{Z}_p^{2k}$ is a fresh random value for each instance. Actually, they show that $[\mathbf{k}_0^\top \mathbf{t}]_1$ is pseudorandom.

In this paper, we are going to present an approach to obtain malleability for this pseudorandom function, which we use as one part of our signature, and the NIZK proof as another part. Therefore, we first add a tag (to allow a homomorphism on the pseudorandom part) to our signature, such that everyone who knows it can re-randomize the pseudorandom part. Second, we revise the NIZK proof and give a proof for well-formedness of both the pseudorandom part and the tag, such that it can be re-randomized and that we finally get a fresh signature, including fresh pseudorandom part and a proof for it. More precisely, we first show that for all $[\mathbf{t}]_1 = [\mathbf{A}_0]_1 \mathbf{r}_1$ and $[\mathbf{w}]_1 = [\mathbf{A}_0]_1 \mathbf{r}_2$ for $\mathbf{r}_1, \mathbf{r}_2 \xleftarrow{R} \mathbb{Z}_p^k$ chosen freshly for each instance, and a NIZK proof π for $\mathbf{t}, \mathbf{w} \in \text{span}(\mathbf{A}_0) \cup \text{span}(\mathbf{A}_1)$ (to be discussed later), the following tuples are indistinguishable under the MDDH assumption

$$(\mathbf{k}_0^\top [\mathbf{t}]_1, \mathbf{k}_0^\top [\mathbf{w}]_1), \quad ((\mathbf{k}_0^\top + \mathbf{s}^\top) [\mathbf{t}]_1, \mathbf{k}_0^\top [\mathbf{w}]_1). \quad (2)$$

We then use this MAC (for $k = 1$)⁶ to construct an SPS-EQ scheme on a message $[\mathbf{m}]_1 \in (\mathbb{G}_1^*)^\ell$. Our signature has a basic form like $\sigma = \mathbf{k}_0^\top [\mathbf{t}]_1 + \mathbf{k}^\top [\mathbf{m}]_1$, with a tag $\tau = \mathbf{k}_0^\top [\mathbf{w}]_1$ (which is only required for randomization), where $\mathbf{k}_0 \xleftarrow{R} \mathbb{Z}_p^2$ and $\mathbf{k} \xleftarrow{R} \mathbb{Z}_p^\ell$. We can use (2) to add some randomness to the signature as $\sigma = \mathbf{k}_0^\top [\mathbf{t}]_1 + \mathbf{k}^\top [\mathbf{m}]_1 + \zeta$ for $\zeta \xleftarrow{R} \mathbb{Z}_p$. At a high level, by adding randomness to each signature, we can make every signature independent of each other. So, we completely hide the values \mathbf{k} , and an adversary has negligible chance to compute a valid forgery. On the other hand, everyone can obtain a fresh tag, using previous tag τ , and add it to the signature to obtain a fresh pseudorandom part. From a high level perspective, we have a basic MAC which is additively homomorphic and our signatures and tags are two instances of it, one on message $[\mathbf{m}]_1$ and another one on message zero. This allows deriving a signature on $\mu[\mathbf{m}]_1$ for $\mu \xleftarrow{R} \mathbb{Z}_p^*$, i.e., to adapt the signature part to representative $\mu[\mathbf{m}]_1$, using a multiplication of the signature part with μ and then add it to the fresh tag. Note that, in our scheme we do not need to have access to the tag τ in the verification algorithm, but it is required for randomizing messages and signatures (changing representatives in the language of SPS-EQ). We note that in the EUF-CMA game, we model it in a way that on a signature query the challenger returns both the signature and the tag, while the adversary only needs to output a signature without the tag as its forgery attempt.

Now, we will discuss how to randomize the NIZK proof. At this point, there is an obvious problem with the OR-proof used in [43] and we need to revise their approach such that the proof is randomizable (proofs can be re-randomized to look like fresh proofs) and malleable (statements for given proofs can be updated), where latter is required to switch between representatives of a class. In particular, to obtain these properties we change a part of the OR-proof and replace it with a QA-NIZK. In the NIZK proof of [43], we have a permanent CRS including $[\mathbf{D}]_2 \in \mathbb{G}_2^2$ and $[\mathbf{z}]_2 \in \mathbb{G}_2^2$, where $\mathbf{z} \notin \text{span}(\mathbf{D})$ be parameters of the system. On the other hand, their scheme has an updatable CRS including $[\mathbf{z}_0]_2$ and $[\mathbf{z}_1]_2$. Now, given the permanent CRS, the complements of the parts of the updatable CRS are computed in each instance. The idea is that exactly these CRS generate a sound system (i.e., one of the parts of the updatable CRS is outside the span of $[\mathbf{D}]_2$) and in the other case we have a simulatable system (i.e., both parts of the updatable CRS are in the span of $[\mathbf{D}]_2$). As the public parameter $[\mathbf{z}]_2$ is not in the span of $[\mathbf{D}]_2$, we can obtain soundness by letting $[\mathbf{z}_0]_2 = [\mathbf{D}]_2 v$ and $[\mathbf{z}_1]_2 = [\mathbf{z}]_2 - [\mathbf{z}_0]_2$, for $v \xleftarrow{R} \mathbb{Z}_p$, where the sum of them is equal to the value $[\mathbf{z}]_2$, i.e., $[\mathbf{z}_0]_2 + [\mathbf{z}_1]_2 = [\mathbf{z}]_2$. So, it proves that at least one of $[\mathbf{z}_0]_2$ and $[\mathbf{z}_1]_2$ has a part in the span(\mathbf{z}). The fact that this sum of the updatable CRS is a fixed value is of course not good to enable the randomization of the updatable CRS. To circumvent this state of affairs and obtain malleability, we need to compute a NIZK proof π for $\mathbf{t}, \mathbf{w} \in \text{span}(\mathbf{A}_0) \cup \text{span}(\mathbf{A}_1)$ with the

⁶ We note that we can only instantiate our construction for $k = 1$, i.e., under the SXDH assumption, and leave the construction of SPS-EQ under the more general Matrix Decision Diffie-Hellman assumption as an interesting open problem.

shared updatable CRS, for \mathbf{t} and \mathbf{w} , and adapt other proof parts, while we remain sound. Our approach is to set $[\mathbf{z}_0]_2 = [\mathbf{D}]_2 v$ and $[\mathbf{z}_1]_2 = [\mathbf{z}]_2 v$, and give a proof using a one-time homomorphic QA-NIZK due to Jutla and Roy [62] that $\mathbf{z}_0 + \mathbf{z}_1$ is in the linear subspace of $\mathbf{D} + \mathbf{z}$. This means that at least one of $[\mathbf{z}_0]_2$ and $[\mathbf{z}_1]_2$ has a part in $\text{span}(\mathbf{z})$. Fortunately, after this change other parts of the proof adapt properly, and only moving to using a QA-NIZK comes at the cost of having computationally soundness instead of perfect soundness.⁷

For realizing the change representative algorithm `ChgRep`, our `Prove` algorithm of the OR-proof computes two proofs with shared randomness and QA-NIZK (where the second proof is part of the tag), which allows to randomize the first proof and update its word. This yields to have randomized signatures output by `ChgRep` to be distributed identical to a fresh signature for the new representative, i.e., we obtain perfect adaption. As explained above, we use a NIZK OR-proof and a QA-NIZK proof in the construction of the SPS-EQ. In order to guarantee perfect adaption even in front of a signer that generates the keys in a potentially malicious way (i.e., remembers a trapdoor), we need to have a CRS for these proof systems.⁸ Consequently, the perfect adaption of our SPS-EQ is guaranteed in the common parameter model where the parameters include a common reference string. However, we stress again that for most applications the CRS generation can simply be part of the key generation and no trusted setup is required.

Comparison with other schemes. In the following Table 1 we provide a

Scheme	Signature	PK	Model	Ass.	Loss	A
[38]	$2 \mathbb{G}_1 + 1 \mathbb{G}_2 $	$\ell \mathbb{G}_2 $	EUFCMA (strong)	GGM	–	✓✓
[35]	$(4\ell + 2) \mathbb{G}_1 + 4 \mathbb{G}_2 $	$(4\ell + 2) \mathbb{G}_2 $	EUFCoMA (weak)	$\mathcal{D}_{4,2}$ -MDDH, \mathcal{D}_1 -KerMDH	$\mathcal{O}(Q)$	\approx
Section 5	$8 \mathbb{G}_1 + 9 \mathbb{G}_2 $	$3\ell \mathbb{G}_2 $	EUFCMA (strong)	SXDH	$\mathcal{O}(\log Q)$	✓

Table 1. Comparison of SPS-EQ and EQS Schemes when signing vectors of length ℓ and Q is the number of queries to the signing oracle. **A** means adaption. ✓✓ means perfect adaption under honest and malicious keys; ✓ means perfect adaption under honest keys and under malicious keys in the honest parameters model (i.e., using a CRS); \approx means adaption under honest keys and honest signatures.

⁷ Thus, we will formally have a NIZK argument, but in the text we will usually not make a distinction between NIZK proofs and arguments.

⁸ Even if all involved proof systems provide zero-knowledge definitions in the style of composable zero-knowledge [50], i.e., even if the adversary knows the trapdoor and still simulated and honestly computed proofs cannot be distinguished, we still have the problem of maliciously generated proofs and thus we cannot avoid a CRS.

comparison of previous SPS-EQ schemes with the one proposed in this paper. We only consider schemes satisfying some reasonable adaption notion, i.e., we exclude the one under q -type assumptions in [39]. We note that while for [38] original and randomized signatures are identical, for [35] and our scheme presented in this paper we only consider sizes of randomized signatures, i.e., those output by **ChgRep** and signatures without the tag respectively. For [35] we consider a concrete setting where $\mathcal{U}_{4,2}$ -MDDH reduces to the SXDLin assumption [2], i.e., assuming DLin in \mathbb{G}_1 and \mathbb{G}_2 , and \mathcal{D}_1 -KerMDH in \mathbb{G}_2 reduces to the DDH assumption in \mathbb{G}_2 . For our scheme $k = 1$ and thus we have the \mathcal{L}_1 -MDDH assumption in \mathbb{G}_1 and the \mathcal{L}_1 -KerMDH assumption in \mathbb{G}_2 . Latter representing the 1-KerLin assumption which by Lemma 1 is implied by DDH. Consequently, our scheme is secure under SXDH, i.e., assuming DDH in \mathbb{G}_1 and \mathbb{G}_2 .

2 Preliminaries

Notation. Let **GGen** be a probabilistic polynomial time (PPT) algorithm that on input 1^λ returns a description $\mathcal{G} = (\mathbb{G}, p, P)$ of an additive cyclic group \mathbb{G} of order p for a λ -bit prime p , whose generator is P . We use implicit representation of group elements as introduced in [31]. For $a \in \mathbb{Z}_p$, define $[a] = aP \in \mathbb{G}$ as the implicit representation of a in \mathbb{G} . We will always use this implicit notation of elements in \mathbb{G} , i.e., we let $[a] \in \mathbb{G}$ be an element in \mathbb{G} , and note that from $[a] \in \mathbb{G}$ it is generally hard to compute the value a (discrete logarithm problem in \mathbb{G}).

Let **BGGen** be a PPT algorithm that returns a description $\mathbf{BG} = (\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, p, P_1, P_2, e)$ of an asymmetric bilinear group where $\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T$ are cyclic groups of order p , P_1 and P_2 are generators of \mathbb{G}_1 and \mathbb{G}_2 , respectively, and $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T$ is an efficiently computable (non-degenerate) bilinear map and for $s \in \{1, 2, T\}$ and $a \in \mathbb{Z}_p$, analogous to above, we write $[a]_s = aP_s \in \mathbb{G}_s$ as the implicit representation of a in \mathbb{G}_s . For two matrices (vectors) \mathbf{A}, \mathbf{B} define $e([\mathbf{A}]_1, [\mathbf{B}]_2) := [\mathbf{AB}]_T \in \mathbb{G}_T$. With $\overline{\mathbf{B}}$ we denote the upper square matrix of \mathbf{B} . Let $r \xleftarrow{R} \mathcal{S}$ denotes sampling r from set \mathcal{S} uniformly at random. We denote by λ the security parameter, and by ϵ any negligible function of λ .

Assumptions. We recall the definition of the Matrix Decision Diffie-Hellman assumption [31] and a natural computational analogue of it, called the Kernel-Diffie-Hellman assumption [70].

Definition 1 (Matrix Distribution). Let $k \in \mathbb{N}$. We call \mathcal{D}_k a matrix distribution if it outputs matrices in $\mathbb{Z}_q^{(k+1) \times k}$ of full rank k in polynomial time.

Definition 2 (\mathcal{D}_k -Matrix Decision Diffie-Hellman Assumption). Let \mathcal{D}_k be a matrix distribution. We say that the \mathcal{D}_k -Matrix Diffie-Hellman (\mathcal{D}_k -MDDH) Assumption holds relative to **BGGen** in group \mathbb{G}_s if for all PPT adversaries \mathcal{A} , we have:

$$\begin{aligned} \mathbf{Adv}_{\mathcal{D}_k, \mathbb{G}_s}^{\text{MDDH}}(\mathcal{A}) := & |\Pr[\mathcal{A}(\mathbf{BG}, [\mathbf{A}]_s, [\mathbf{Aw}]_s) = 1] \\ & - \Pr[\mathcal{A}(\mathbf{BG}, [\mathbf{A}]_s, [\mathbf{u}]_s) = 1]| \leq \epsilon(\lambda) \end{aligned}$$

where the probability is taken over $\text{BG} \leftarrow \text{BGGen}(1^\lambda)$, $\mathbf{A} \leftarrow \mathcal{D}_k$, $\mathbf{w} \leftarrow \mathbb{Z}_q^k$, $\mathbf{u} \leftarrow \mathbb{Z}_q^{k+1}$

Definition 3 (Kernel Matrix Diffie-Hellman Assumption). Let \mathcal{D}_k be a matrix distribution and $s \in \{1, 2\}$. We say that the \mathcal{D}_k -Kernel Diffie-Hellman Assumption (\mathcal{D}_k -KerMDH) holds relative to BGGen in group \mathbb{G}_s if for all PPT adversaries \mathcal{A} ,

$$\text{Adv}_{\mathcal{D}_k, \mathbb{G}_s}^{\text{KerMDH}}(\mathcal{A}) = \Pr \left[[\mathbf{c}]_{3-s} \leftarrow \mathcal{A}(\text{BG}, [\mathbf{A}]_s) : \mathbf{c}^\top \mathbf{A} = \mathbf{0} \wedge \mathbf{c} \neq \mathbf{0} \right] \leq \epsilon(\lambda)$$

where $\mathbf{A} \xleftarrow{R} \mathcal{D}_k$.

Lemma 1 (\mathcal{D}_k -MDDH \implies \mathcal{D}_k -KerMDH [70]). Let $k \in \mathbb{N}$ and let \mathcal{D}_k be a matrix distribution. For any PPT adversary \mathcal{A} , there exists a PPT adversary \mathcal{B} such that $\text{Adv}_{\mathcal{D}_k, \mathbb{G}_s}^{\text{KerMDH}}(\mathcal{A}) \leq \text{Adv}_{\mathcal{D}_k, \mathbb{G}_s}^{\text{MDDH}}(\mathcal{B})$.

2.1 Structure-Preserving Signatures on Equivalence Classes

In this section, we recall the definition and the security model of SPS-EQ scheme, as introduced in [52]. We note that in order to cover a broader range of potential constructions, we rename the algorithm BGGen that generates the bilinear group BG to ParGen generating public parameters par , i.e., now the parameters par can potentially include additional values such as a common reference string. Moreover, our construction is tag-based where the tag output by Sign is just used as input to ChgRep , where no new tag is output, and required for randomization (for normal SPS-EQ, every occurrence of the tag τ is just ignored).

Definition 4 (SPS-EQ). A SPS-EQ scheme is tuple of PPT algorithms:

- $\text{ParGen}(1^\lambda)$. On security parameter λ and returns par including an asymmetric bilinear group BG . par is implicitly used as input by all of the algorithms.
- $\text{KeyGen}(\text{par}, \ell)$: This algorithm takes pp and vector length $\ell > 1$ as input and outputs a key pair (sk, pk) .
- $\text{Sign}([\mathbf{m}]_i, \text{sk})$: This algorithm given a representative $[\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell$ for class $[\mathbf{m}]_{\mathcal{R}}$ and a secret key sk outputs a signature $\sigma' = (\sigma, \tau)$ (potentially including a tag τ).
- $\text{ChgRep}([\mathbf{m}]_i, (\sigma, \tau), \mu, \text{pk})$: This algorithm on input a representative $[\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell$ and signature σ (and potentially a tag τ), a scalar μ and pk as public key, computes an updated signature σ' on new representative $[\mathbf{m}']_i = [\mu \mathbf{m}]_i$ and returns $([\mathbf{m}']_i, \sigma')$.
- $\text{Verify}([\mathbf{m}]_i, (\sigma, \tau), \text{pk})$: This verification algorithm when given a representative $[\mathbf{m}]_i$, a signature σ (potentially including a tag τ) and public key pk , outputs 1 if it accepts and 0 otherwise.
- $\text{VKey}(\text{sk}, \text{pk})$: This algorithm on input key pair (sk, pk) outputs 1 if secret key and public key are consistent and 0 otherwise.

We recall correctness, EUF-CMA security and the notion of perfect adaption (latter being a stronger notion than the original class-hiding notion which we omit here).

Definition 5 (Correctness). An SPS-EQ over $(\mathbb{G}_i^*)^\ell$ correct if for any $\lambda \in N$, any $\ell > 1$, any $\text{par} \leftarrow \text{ParGen}(1^\lambda)$, any pair $(\text{sk}, \text{pk}) \leftarrow \text{KeyGen}(\text{par}, \ell)$, any message $[\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell$ and any $\mu \in \mathbb{Z}_p$ the following holds:

$$\begin{aligned} \text{VKey}(\text{sk}, \text{pk}) &= 1, \text{ and} \\ \Pr[\text{Verify}([\mathbf{m}]_i, \text{Sign}([\mathbf{m}]_i, \text{sk}), \text{pk}) = 1] &= 1, \text{ and} \\ \Pr[\text{Verify}(\text{ChgRep}([\mathbf{m}]_i, \text{Sign}([\mathbf{m}]_i, \text{sk}), \mu, \text{pk}), \text{pk}) = 1] &= 1. \end{aligned}$$

Definition 6 (EU-CMA). An SPS-EQ over $(\mathbb{G}_i^*)^\ell$ is existentially unforgeable under adaptively chosen-message attacks, if for all $\ell > 1$ and PPT adversaries \mathcal{A} with access to a signing oracle $\mathcal{O}^{\text{Sign}}$, there is a negligible function $\epsilon(\cdot)$:

$$\Pr \left[\begin{array}{l} \text{par} \leftarrow \text{ParGen}(1^\lambda), \\ (\text{sk}, \text{pk}) \leftarrow \text{KeyGen}(\text{par}, \ell), \\ ([\mathbf{m}]_i^*, \sigma^*) \leftarrow \mathcal{A}^{\mathcal{O}^{\text{Sign}}(\text{sk}, \cdot)}(\text{pk}) \end{array} : \begin{array}{l} [\mathbf{m}^*]_{\mathcal{R}} \neq [\mathbf{m}]_{\mathcal{R}} \quad \forall [\mathbf{m}]_i \in Q^{\text{Sign}} \wedge \\ \text{Verify}([\mathbf{m}]_i^*, \sigma^*, \text{pk}) = 1 \end{array} \right] \leq \epsilon(\lambda),$$

where $Q^{\text{Sign}\mathcal{R}}$ is the set of queries that \mathcal{A} has issued to the signing oracle $\mathcal{O}^{\text{Sign}}$. Note that in the tag-based case this oracle returns (σ_i, τ_i) .

Perfect adaption introduced in [39] by Fuchsbauer et al. requires signatures output by ChgRep are distributed like fresh signatures on the new representative. We present both variants here, as we will require them later. We do not yet adapt them to the tag-based variant of SPS-EQ (this is done afterwards). Note that in the following variant signatures are only required to verify (so may be maliciously computed) while we only consider keys need to satisfy VKey .

Definition 7 (Perfect adaption of signatures). An SPS-EQ over $(\mathbb{G}_i^*)^\ell$ perfectly adapts signatures if for all tuples $(\text{sk}, \text{pk}, [\mathbf{m}]_i, \sigma, \mu)$ with:

$$\text{VKey}(\text{sk}, \text{pk}) = 1 \quad \text{Verify}([\mathbf{m}]_i, \sigma, \text{pk}) = 1 \quad [\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \mu \in \mathbb{Z}_p^*$$

we have that $\text{ChgRep}([\mathbf{m}]_i, \sigma, \mu, \text{pk})$ and $([\mu \cdot \mathbf{m}]_i, \text{Sign}([\mu \cdot \mathbf{m}]_i, \text{sk}))$ are identically distributed.

In the subsequent definition, the strongest adaption notion, one in addition to potentially maliciously generated signatures one also considers maliciously generated keys (i.e., does not require that VKey needs to hold).

Definition 8 (Perfect adaption of signatures under malicious keys). An SPS-EQ over $(\mathbb{G}_i^*)^\ell$ perfectly adapts signatures under malicious keys if for all tuples $(\text{pk}, [\mathbf{m}]_i, \sigma, \mu)$ with:

$$[\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \text{Verify}([\mathbf{m}]_i, \sigma, \text{pk}) = 1 \quad \mu \in \mathbb{Z}_p^*$$

we have that ChgRep outputs $([\mu \cdot \mathbf{m}]_i, \sigma')$ such that σ' is a random element in the space of signatures, conditioned on $\text{Verify}([\mu \cdot \mathbf{m}]_i, \sigma', \text{pk}) = 1$.

Perfect adaption in context of a CRS and for tag-based SPS-EQ. If par contains a CRS (as in the case of our construction), we need to consider this in the adaption notion. For Definition 7 we just replace $(\text{sk}, \text{pk}, [\mathbf{m}]_i, \sigma, \mu)$ with $(\text{par}, \text{sk}, \text{pk}, [\mathbf{m}]_i, \sigma, \mu)$ where $\text{par} \leftarrow \text{ParGen}(1^\lambda)$ is honestly generated. We introduce it subsequently, for completeness.

Definition 9 (Perfect adaption in the honest parameter model). *An SPS-EQ scheme $(\text{ParGen}, \text{Sign}, \text{ChgRep}, \text{Verify}, \text{VKey})$ perfectly adapts signatures if for all $(\text{par}, \text{sk}, \text{pk}, [\mathbf{m}]_i, \sigma, \tau, \mu)$ with*

$$\begin{aligned} \text{VKey}(\text{sk}, \text{pk}) = 1 \quad \text{Verify}([\mathbf{m}]_i, (\sigma, \tau), \text{pk}) = 1 \quad [\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \mu \in \mathbb{Z}_p^* \\ \text{par} \leftarrow \text{ParGen}(1^\lambda) \end{aligned}$$

the following are identically distributed:

$$\begin{aligned} (\sigma, \text{ChgRep}([\mathbf{m}]_i, \sigma, \tau, \mu, \text{pk})) \text{ and} \\ ((\sigma', \cdot) \leftarrow \text{Sign}(\text{sk}, [\mathbf{m}]_i), \text{ChgRep}([\mathbf{m}]_i, \text{Sign}(\text{sk}, [\mu \cdot \mathbf{m}]_i), 1, \text{pk})) \end{aligned}$$

Definition 8 does not change and also considers a potentially malicious generation of the parameters which may include a CRS (which is not satisfied by our construction). Moreover, we introduce an intermediate notion, where keys may be generated maliciously, but par is generated honestly. We formally define it in the following for completeness (this is satisfied by our construction).

Definition 10 (Perfect adaption of signatures under malicious keys in the honest parameters model). *An SPS-EQ over $(\mathbb{G}_i^*)^\ell$ perfectly adapts signatures under malicious keys in the honest parameter model if for all tuples $(\text{par}, \text{pk}, [\mathbf{m}]_i, \sigma, \tau, \mu)$ with:*

$$[\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \text{Verify}([\mathbf{m}]_i, (\sigma, \tau), \text{pk}) = 1 \quad \mu \in \mathbb{Z}_p^* \quad \text{par} \leftarrow \text{ParGen}(1^\lambda)$$

we have that ChgRep outputs $([\mu \cdot \mathbf{m}]_i, \sigma')$ such that σ' is a random element in the space of signatures, conditioned on $\text{Verify}([\mu \cdot \mathbf{m}]_i, \sigma', \text{pk}) = 1$.

2.2 Non-Interactive Zero-Knowledge Proofs

Let $\mathcal{R}_{\mathcal{L}}$ be an efficiently computable relation of pairs (x, w) of words and witnesses. Let \mathcal{L} be the language defined as $\mathcal{L} = \{x \mid \exists w : \mathcal{R}_{\mathcal{L}}(x, w) = 1\}$. We recall the definition of a NIZK proof system [19] for a relation $\mathcal{R}_{\mathcal{L}}$, where we use the formalization in [43] (based on [50]) for the sake of consistency. We note that we focus on NIZK argument systems, where soundness only holds for computationally bounded adversaries.

- $\text{PGen}(1^\lambda, \text{par})$: On input a security parameter λ and parameters par outputs a common reference string crs .
- $\text{PTGen}(1^\lambda, \text{par})$: On input a security parameter λ and parameters par outputs a common reference string crs and a trapdoor td .

- $\text{PPro}(\text{crs}, x, w)$: On input a common reference string crs , a statement x , and a witness w such that $\mathcal{R}_{\mathcal{L}}(x, w) = 1$, returns a proof Ω .
- $\text{PVer}(\text{crs}, x, \Omega)$: On input a reference string crs and a proof Ω , Returns accept if Ω is valid and reject otherwise.
- $\text{PSim}(\text{crs}, \text{td}, x)$: On input common reference string crs , and the trapdoor td and word x and outputs a simulated proof Ω .

A NIZK argument system needs to satisfy the following properties:

- **Perfect Completeness:** For all possible public parameters par , all $\lambda \in \mathbb{N}$, all words $x \in \mathcal{L}$, and all witnesses w such that $\mathcal{R}_{\mathcal{L}}(x, w) = 1$, we have

$$\Pr \left[\begin{array}{l} \text{crs} \leftarrow \text{PGen}(1^\kappa, \text{par}), \\ \Omega \leftarrow \text{PPro}(\text{crs}, x, w) \end{array} : \text{PVer}(\text{crs}, x, \Omega) = 1 \right] = 1.$$

- **Computational Soundness:** For all PPT adversaries \mathcal{A} and for all words $x \notin \mathcal{L}$ we have:

$$\Pr \left[\begin{array}{l} \text{crs} \leftarrow \text{PGen}(1^\kappa, \text{par}), \\ \Omega \leftarrow \mathcal{A}(\text{crs}, x) \end{array} : \text{PVer}(\text{crs}, x, \Omega) = 0 \right] \approx 1.$$

- **Composable Zero-Knowledge:** For all PPT adversaries \mathcal{A} , we have

$$\Pr [\text{crs} \leftarrow \text{PGen}(1^\lambda, \text{par}) : \mathcal{A}(1^\lambda, \text{crs}) = 1] \approx$$

$$\Pr [(\text{crs}, \text{td}) \leftarrow \text{PTGen}(1^\lambda, \text{par}) : \mathcal{A}(1^\lambda, \text{crs}) = 1].$$

Furthermore, for all for all $x \in \mathcal{L}$ with witness w such that $\mathcal{R}_{\mathcal{L}}(x, w) = 1$, the following are identically distributed:

$$\text{PPro}(\text{crs}, x, w) \quad \text{and} \quad \text{PSim}(\text{crs}, \text{td}, x)$$

where $(\text{crs}, \text{td}) \leftarrow \text{PTGen}(1^\lambda, \text{par})$. Note that the composable zero knowledge requires indistinguishability even for adversaries that get access to $(\text{crs}, \text{trap})$.

Quasi-Adaptive NIZK proofs. Quasi-Adaptive NIZK (QA-NIZK) proofs [61, 67, 62, 65, 47, 8, 28] are NIZK proofs where the generation of the common reference string (CRS), for a class of languages \mathcal{L}_ρ , parametrized by ρ , is allowed to depend on the language parameter ρ . Moreover the common CRS includes a fixed part par , generated by an algorithm pargen . Here, we recall the definitions QA-NIZK proofs, as presented in [65].

Definition 11 (QA-NIZK). A non-interactive proof system $(\text{pargen}, \text{crsgen}, \text{prove}, \text{verify}, \text{sim})$ is said to be a QA-NIZK proof system for an ensemble of distributions $\{\mathcal{D}_{\text{par}}\}$ on collection of witness-relations $\mathcal{R} = \{\mathcal{R}_\rho\}$ with associated language parameter ρ if the following holds (cf. [65]):

Perfect Completeness: For all λ , all par output by $\text{pargen}(1^\lambda)$, all ρ output by \mathcal{D}_{par} , all (x, y) with $\mathcal{R}_\rho(x, y) = 1$, we have

$$\Pr \left[\begin{array}{l} (\text{crs}, \text{trap}) \leftarrow \text{crsgen}(\text{par}, \rho), \\ \pi \leftarrow \text{prove}(\text{crs}, x, w) \end{array} : \text{verify}(\text{crs}, x, \pi) = 1 \right] = 1$$

Computational Adaptive Soundness: For all PPT adversaries \mathcal{A} ,

$$\Pr \left[\begin{array}{l} \rho \leftarrow \mathcal{D}_{\text{par}}, \text{par} \leftarrow \text{pargen}(1^\lambda), \\ \text{crs} \leftarrow \text{crsgen}(\text{par}, \rho), \\ (x, \pi) \leftarrow \mathcal{A}_1(\text{crs}, \text{par}, \rho) \end{array} : \begin{array}{l} \text{verify}(\text{crs}, x, \pi) = 1 \wedge \\ x \notin \mathcal{L}_\rho \end{array} \right] \leq \epsilon(\lambda)$$

Perfect Zero-Knowledge: For all λ , all par output by $\text{pargen}(1^\lambda)$, all ρ output by \mathcal{D}_{par} , all $(\text{crs}, \text{trap})$ output by $\text{crsgen}(\text{par}, \rho)$, all (x, y) with $\mathcal{R}_\rho(x, y) = 1$, the distributions

$$\text{prove}(\text{crs}, x, w) \quad \text{and} \quad \text{sim}(\text{crs}, \text{td}, x)$$

are identical. Note that the formalization of perfect zero-knowledge is similar to that of composable zero knowledge in [50] and requires indistinguishability even for adversaries that get access to $(\text{crs}, \text{trap})$.

2.3 Malleable Proof Systems

Let $\mathcal{R}_\mathcal{L}$ be the witness relation associated to language \mathcal{L} , then a controlled malleable proof system [24] is accompanied by a family of efficiently computable n -ary transformations $T = (T_x, T_w)$ such that for any n -tuple $\{(x_1, w_1), \dots, (x_n, w_n)\} \in \mathcal{R}_\mathcal{L}^n$ it holds that $(T_x(x_1, \dots, x_n), T_w(w_1, \dots, w_n)) \in \mathcal{R}_\mathcal{L}$ (the family of admissible transformations is denoted by \mathcal{T}). Intuitively, such a proof system allows when given valid proofs $\{\Omega_i\}_{i \in [n]}$ for words $\{x_i\}_{i \in [n]}$ with associated witnesses $\{w_i\}_{i \in [n]}$ to publicly compute a valid proof Ω for word $x := T_x(x_1, \dots, x_n)$ corresponding to witness $w := T_w(w_1, \dots, w_n)$ using an additional algorithm denoted as ZKEval . More formally, the additional algorithms is defined as follows:

- $\text{ZKEval}(\text{crs}, T, (x_i, \Omega_i)_{i \in [n]})$: takes as input common reference string crs , a transformation $T \in \mathcal{T}$, words x_1, \dots, x_n and corresponding proofs $\Omega_1, \dots, \Omega_n$, and outputs a new word $x' := T_x(x_1, \dots, x_n)$ and proof Ω' .

It is desirable that proofs computed by applying ZKEval are indistinguishable from freshly computed proofs for the resulting word $x' := T_x(x_1, \dots, x_n)$ and corresponding witness $w' := T_w(w_1, \dots, w_n)$ (this property is called (strong) derivation privacy). We recall the weaker notion of derivation privacy below.

Definition 12 (Derivation Privacy [24]). A NIZK proof system $\{\text{PGen}, \text{PTGen}, \text{PPro}, \text{PVer}, \text{PSim}, \text{ZKEval}\}$ being malleable with respect to a set of transformations \mathcal{T} defined on some relation \mathcal{R} is derivation private, if for all PPT adversaries \mathcal{A} ,

$$\Pr \left[\begin{array}{l} \text{crs} \leftarrow \text{PGen}(1^\kappa), b \xleftarrow{R} \{0, 1\}, \\ (\text{st}, ((x_i, w_i), \Omega_i)_{i \in [q]}, T) \leftarrow \mathcal{A}(\text{crs}), \\ \text{Return } \perp \text{ if } (T \notin \mathcal{T} \vee \exists i \in [q] : (\text{PVer}(\text{crs}, x_i, \Omega_i) = 0 \vee \\ (x_i, w_i) \notin \mathcal{R})), \\ \text{Else if } b = 0 : \Omega \leftarrow \text{PPro}(\text{crs}, T_x((x_i)_{i \in [q]}), T_w((w_i)_{i \in [q]})), \quad : b = b^* \\ \text{Else if } b = 1 : \Omega \leftarrow \text{ZKEval}(\text{crs}, T, (x_i, \pi_i)_{i \in [q]}), \\ b^* \leftarrow \mathcal{A}(\text{st}, \Omega) \end{array} \right] \leq \epsilon(\lambda)$$

3 Revisiting the FG18 Model and Applications

In this section we recall the construction in [35] (denoted FG18 henceforth) and point out some issues regarding their signature adaption notion and the implicitly assumed notion of perfect composition from [51] for concrete applications. We again stress that FG18 scheme is secure in FG18 model (honestly signature and key generation or semi-honest), but we are going to show its problems in the stronger model, which is current acceptable model. In order to make it more convenient for the reader we adapt the notion used in [35] to the original SPS-EQ notion (but keep their name EQS).

First, we recall that their scheme has a one-time randomizability property and therefore FG18 need to modify the perfect adaption notion from [39] (Definition 7 in Section 2.1) to exclude trivial distinguishers, i.e., they always consider the pairs of original and adapted signatures in their distributions. We recall their version in Definition 13. The most important difference⁹ is that while the original notion in Definition 7 considers maliciously generated signatures, the definition in [35] is restricted to *honestly generated* signatures.

Definition 13 (Signature Adaption [35]). *An EQS scheme (ParGen, Sign, ChgRep, Verify, VKey) perfectly adapts signatures if for all $(\text{sk}, \text{pk}, [\mathbf{m}]_i, \mu)$ with*

$$\text{VKey}(\text{sk}, \text{pk}) = 1 \quad [\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \mu \in \mathbb{Z}_p^*$$

the following are identically distributed:

$$(\rho := \text{Sign}(\text{sk}, [\mathbf{m}]_i), \text{ChgRep}(\text{pk}, \rho, \mu)) \text{ and}$$

$$(\rho := \text{Sign}(\text{sk}, [\mathbf{m}]_i), \text{ChgRep}(\text{pk}, \text{Sign}(\text{sk}, [\mu \cdot \mathbf{m}]_i), 1))$$

In Figure 1 we recall the FG18 scheme and then proceed to discuss problems of Definition 13 and their scheme in context of applications.

3.1 Problem With Key Verification and the Need for a CRS

Fuchsbauer and Gay require for signature adaption that the respective EQS scheme provides a VKey algorithm that checks consistency of keys sk and pk . When looking at their keys $\text{pk} := ([\mathbf{B}]_2, \{[\mathbf{K}_i \mathbf{B}]_2\}_{i \in [\ell]})$ and $\text{sk} := (\mathbf{A}, \{\mathbf{K}_i\}_{i \in \ell})$, a potential VKey algorithm can check the consistency of pk with the part of the secret key $\{\mathbf{K}_i\}_{i \in \ell}$. They did not specify the VKey algorithm, but any reasonable VKey would check if sk contains the trapdoor \mathbf{B} , as honest keys would not contain it. Now an interesting aspect is that this does not per se present a problem in their definition, as they do not consider perfect adaption under malicious keys (in the vein of Definition 8; cf. Section 2.1). However, the existence of the potential trapdoor \mathbf{B} and no means to proving the absence of it represents a problem with

⁹ One syntactical difference is that for EQS they do not input the message $[\mathbf{m}]_i$ in their ChgRep algorithm, but this does not matter for our discussion.

<p>Setup(\mathcal{PG}) :</p> <hr style="border: 0.5px solid black;"/> $\mathbf{A} \xleftarrow{R} \mathcal{D}_{2k,k}, \mathbf{B} \xleftarrow{R} \mathcal{D}_{k'}$ for $i \in [\ell]$ do $\mathbf{K}_i \xleftarrow{R} \mathbb{Z}_p^{2k \times (k'+1)}$ endfor $\text{pk} := ([\mathbf{B}]_2, \{[\mathbf{K}_i \mathbf{B}]_2\}_{i \in [\ell]})$ $\text{sk} := (\mathbf{A}, \{\mathbf{K}_i\}_{i \in [\ell]})$ return (pk,sk)	<p>Sign(sk, $[\mathbf{m}]_1 \in (\mathbb{G}_1^\ell)^*$) :</p> <hr style="border: 0.5px solid black;"/> $\mathbf{U} \xleftarrow{R} \text{GL}_k, \mathbf{S} = \mathbf{A}\mathbf{U}$ for $i \in [\ell]$ do $[\mathbf{S}_i]_1 = [m_i]_1 \mathbf{S}$ endfor $[\mathbf{S}_{\ell+1}]_1 = \sum_{i=1}^{\ell} [m_i]_1 \mathbf{K}_i^\top \mathbf{S}$ return $\rho = (\{[\mathbf{S}_i]_1\}_{i \in [\ell+1]}, [\mathbf{S}]_2)$
<p>ChgRep(pk, $\rho = (\{[\mathbf{S}_i]_1\}_{i \in [\ell+1]}, [\mathbf{S}]_2), \mu$) :</p> <hr style="border: 0.5px solid black;"/> $\mathbf{r} \xleftarrow{R} (\mathbb{Z}_p^k)^*, [\mathbf{s}]_2 = [\mathbf{S}]_2 \mathbf{r}$ for $i \in [\ell+1]$ do $[\mathbf{s}_i]_1 = \mu [\mathbf{S}_i]_1 \mathbf{r}$ endfor return $\sigma = (\{[\mathbf{s}_i]_1\}_{i \in [\ell+1]}, [\mathbf{s}]_2)$	<p>Ver(pk, $[\mathbf{m}]_1, \sigma = (\{[\mathbf{s}_i]_1\}_{i \in [\ell+1]}, [\mathbf{s}]_2)$) :</p> <hr style="border: 0.5px solid black;"/> if $[\mathbf{s}]_2 \neq [\mathbf{0}]_2$ and $\forall i \in [\ell] : [\mathbf{s}_i]_1 \cdot [1]_2 = [m_i]_1 \cdot [\mathbf{s}]_2$ and $\sum_{i=1}^{\ell} [\mathbf{s}_i]_1 \cdot [\mathbf{K}_i \mathbf{B}]_2 = [\mathbf{s}_{\ell+1}]_1 \cdot [\mathbf{B}]_2$ return 1 else return 0

Fig. 1. EQS Scheme from [35].

the application of the FG18 scheme to attribute-based credentials (ABCs) (cf. Section 5 in [35]).

In the ABC construction from [40], the issuer generates an SPS-EQ key pair and in the `Issue` protocol, the issuer needs to provide a ZKPoK that $\text{VKey}(\text{sk}, \text{pk}) = 1$. Note that for FG18 no realization of this ZKPoK can prove the absence of \mathbf{B} (as the issuer could simply pretend to not knowing it and the ZKPoK cannot cover this) and a malicious issuer may remember \mathbf{B} . Now in the anonymity proof of the ABC scheme (Theorem 8 in [40]), the reduction can extract the signing key sk from the ZKPoK and in the transition from **Game**₁ to **Game**₂, for all calls to the oracle \mathcal{O}_{LoR} the computation of `ChgRep` is replaced with `Sign` of the SPS-EQ, i.e., instead of adapting existing signatures fresh signatures are computed. Now, this is argued under their signature adaption notion. However, without additional means, by the strategy we discuss below (i.e., a way to construct malicious signatures that verify), an adversary can detect with overwhelming probability that the simulation deviates from the original anonymity game and thus this proof breaks down when instantiated with EQS in [35]. The reason is, that their adaption notion in Definition 13 is too weak to be useful to constructing ABCs following the approach in [40].

Attack strategy. Let us assume that the adversary who generates the key-pair $\text{pk} = ([\mathbf{B}]_2, \{[\mathbf{K}_i \mathbf{B}]_2\}_{i \in [\ell]})$ and $\text{sk} = (\mathbf{A}, \{\mathbf{K}_i\}_{i \in [\ell]})$ remembers the trapdoor \mathbf{B} . For simplicity we set $k = 2$ and $k' = 1$ in Scheme 1 and so we have $\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}$. Let us for the sake of exposition assume that the signer (credential issuer) wants to track a specific instance of signing (issuing) and

generates all signatures honestly, except for the one instance (lets say Alice's credential). Latter signature is computed differently by the issuer, but in a way that it is indistinguishable for verifiers, i.e., it still verifies correctly. Actually, instead of computing $\mathbf{S}_{\ell+1} = \begin{pmatrix} S_1 & S_2 \\ S_3 & S_4 \end{pmatrix}$ as dictated by the Sign algorithm (cf. Figure 1), he uses $\mathbf{S}_{\ell+1}$ (as in Sign) but also his trapdoor \mathbf{B} to compute $\mathbf{S}'_{\ell+1} = \begin{pmatrix} S_1 - b_2 & S_2 + b_2 \\ S_3 + b_1 & S_4 - b_1 \end{pmatrix}$. Then, he includes $\mathbf{S}'_{\ell+1}$ instead of $\mathbf{S}_{\ell+1}$ in the first part of the signature ρ . Note that we have $\mathbf{S}_{\ell+1}^\top \mathbf{B} = \mathbf{S}'_{\ell+1}^\top \mathbf{B}$, and for a verifier this alternative signature computation is not noticeable. When Alice wants to randomize ρ (i.e., run ChgRep in Figure 1), she chooses $\mathbf{r} \xleftarrow{R} \mathbb{Z}_p^2$ and obtains $\mathbf{s}'_{\ell+1} = \mu \mathbf{S}'_{\ell+1} \mathbf{r} = \mu \begin{pmatrix} (S_1 - b_2)r_1 + (S_2 + b_2)r_2 \\ (S_3 + b_1)r_1 + (S_4 - b_1)r_2 \end{pmatrix}$. Note that the signer knows \mathbf{K}_i , and so he can check for any given randomized signature the following:

$$\sum_{i=1}^{\ell} [\mathbf{s}_i^\top]_1 \mathbf{K}_i = [\mathbf{s}'_{\ell+1}^\top]_1 \quad (3)$$

which does not use pairing evaluations and thus does not eliminate \mathbf{B} . Now it is easy to see that all randomized signatures including the randomized signature issued for Alice pass the original verification using Ver. However, the randomized signature of Alice has an additional part (i.e., \mathbf{B}) and so Equation (3) cannot be satisfied. So, the signer can easily distinguish the signature issued to Alice from all other honestly computed signatures.

Trying to fix the problem. A modification of the FG18 scheme to prevent this attack would be to put $[\mathbf{B}]_2$ in a common reference string (CRS) used by all signers when generating their keys so that no signer knows \mathbf{B} . As we show subsequently, however, the adaption notion in Definition 13 used for FG18 still remains too weak for ABCs and group signatures.

3.2 Distinguishing Signatures

Now, we show how a malicious signer can distinguish signatures even if keys are generated honestly. In the case of dynamic group signatures (GS) in [30] (or ABCs under honest keys), the adversary in the anonymity game is allowed to compute signatures on its own and we will show how this enables the adversary to track signatures, which breaks the anonymity proof. We stress that this attack works independently of whether there is a trapdoor in the secret key, as the GS in [30] rely on the BSZ model [15] and thus assume honest key generation (mitigating the attack in Section 3.1 by construction).

Attack strategy. First we show how a signer who remembers \mathbf{S} during running Sign can obtain the value of $[\mathbf{r}]_2$, which was used as a randomizer for the signature during ChgRep, and then how he can use it to distinguish two signatures. Again,

let us set $k = 2$ and $k' = 1$. So, we have $\mathbf{S} = \begin{pmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \\ S_7 & S_8 \end{pmatrix}$, and when ChgRep multiplies $[\mathbf{S}]_2$ on $\mathbf{r} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}$, we receive $[\mathbf{s}]_2 = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}_2 = \begin{bmatrix} r_1 S_1 + r_2 S_2 \\ r_1 S_3 + r_2 S_4 \\ r_1 S_5 + r_2 S_6 \\ r_1 S_7 + r_2 S_8 \end{bmatrix}_2$. Taking

$[\mathbf{s}]_2$ and \mathbf{S} , we compute $[\frac{s_1}{S_1}]_2 - [\frac{s_2}{S_3}]_2$, and then multiply it to $(\frac{S_2}{S_1} - \frac{S_4}{S_3})^{-1}$ to obtain $[r_2]_2$. Now, we also can recover $[r_1]_2$ and so we obtain $[\mathbf{r}]_2$.

Now, let the signer generate two signatures, say for Alice and Bob, where he later wants to link the received randomized signature to one of them.

The signer picks $\mathbf{S} = \begin{pmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \\ S_7 & S_8 \end{pmatrix}$ for Alice, and picks different S'_5, S'_6, S'_7, S'_8 ,

and sets $\mathbf{S}' = \begin{pmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S'_5 & S'_6 \\ S'_7 & S'_8 \end{pmatrix}$ for Bob in their respective signatures. When the signer

receives $[\mathbf{s}]_2$, a candidate for a signature obtained from ChgRep , based on the approach discussed above he obtains $[\mathbf{r}]_2$. Now he checks whether $[s_3]_2 = [r_1 S_5 + r_2 S_6]_2$ holds, in which case the randomized signature is related to Alice. On the other hand, if $[s_3]_2 = [r_1 S'_5 + r_2 S'_6]_2$ holds, then the randomized signature is related to Bob.

3.3 No Perfect Composition

Subsequently, in Definition 14 we recall the perfect composition notion from [51] required to construct VES from SPS-EQ. This notion intuitively requires that ChgRep executed with random coins fixed to 1 updates only the parts of the given signature that are affected by updating the representative from $[\mathbf{m}]_i$ to $\mu[\mathbf{m}]_i$ and not changing the randomness ω previously used by Sign .

Definition 14 (Perfect Composition [51]). *An SPS-EQ scheme $(\text{ParGen}, \text{Sign}, \text{ChgRep}, \text{Verify}, \text{VKey})$ allows perfect composition if for all random tapes ω and tuples $(\text{sk}, \text{pk}, [\mathbf{m}]_i, \sigma, \mu)$:*

$$\text{VKey}(\text{sk}, \text{pk}) = 1 \quad \sigma \leftarrow \text{Sign}([\mathbf{m}]_i, \text{sk}; \omega) \quad [\mathbf{m}]_i \in (\mathbb{G}_i^*)^\ell \quad \mu \in \mathbb{Z}_p^*$$

it holds that $(\mu[\mathbf{m}]_i, \text{Sign}(\mu[\mathbf{m}]_i, \text{sk}; \omega)) = \text{ChgRep}([\mathbf{m}]_i, \sigma, \mu, \text{pk}; 1)$.

Since this notion does not require any assumption on the distribution of original and adapted signatures, the issues discussed so far do not yield to any problem. However, it is quite easy to see that this notion is not satisfied by the FG18 scheme and this is actually an inherent problem for EQS (SPS-EQ) schemes where signatures output by Sign and ChgRep have different forms. To illustrate

this for the FG18 scheme (cf. Figure 1), signatures resulting from **Sign** contain a matrix $[\mathbf{S}]_2$, whereas signatures output by **ChgRep** contain the vector $[\mathbf{s}]_2 := [\mathbf{S}]_2 \mathbf{r}$ (where in context of Definition 14, \mathbf{r} represents the all-ones vector).

4 Our OR-Proof and Core Lemma

Subsequently, we present the concrete instantiation of our malleable OR-proof that we use for our SPS-EQ scheme. Firstly, **PPro** computes as a proof two copies Ω_1 and Ω_2 of an OR-proof for statements $[x_1]_1$ and $[x_2]_1$, which use the same randomness v and share a QA-NIZK proof π (denoted by Ω). Consequently, instead of ending up with two independent proofs, we end up with a single proof $\Omega = (\Omega_1 = ([\mathbf{C}_{1,i}]_2, [\mathbf{\Pi}_{1,i}]_1), \Omega_2 = ([\mathbf{C}_{2,i}]_2, [\mathbf{\Pi}_{2,i}]_1), [\mathbf{z}_i]_2, \pi)$ for $i = 0, 1$ where both proofs share $[\mathbf{z}_i]_2$ and π . We also have **PVer** and **PSim** which take two statements and proofs with shared randomness and QA-NIZK denoted by π as input. Our **ZKEval** is restricted to any two words $[\mathbf{x}_1]_1$ and $[\mathbf{x}_2]_1$ corresponding to witnesses r_1 and r_2 where the associated proofs Ω_1 and Ω_2 have been computed using the same randomness v and thus have shared $[\mathbf{z}_i]_2$ and π . The output of **ZKEval** is a proof $\Omega' = (\Omega'_1, [\mathbf{z}_i]_2, \pi')$ for word $[\mathbf{x}'_1]_1$ corresponding to witness $r' = r_1 + \psi r_2$ with $\psi \xleftarrow{R} \mathbb{Z}_p$ chosen by **ZKEval** (i.e., ψ indexes a concrete transformation in the family \mathcal{T}). Finally, we also provide a verification algorithm (**PRVer**) that verifies a single OR-proof (as we use it in the SPS-EQ).

Our OR-proof. Now, we present our malleable proof for OR language $\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee$ based upon the one in [43]. We recall their NIZK proof as well as the QA-NIZK used by us in our NIZK proof in the full version. The language is

$$\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee = \{[\mathbf{x}]_1 \in \mathbb{G}_1^{2k} \mid \exists \mathbf{r} \in \mathbb{Z}_p^k : [\mathbf{x}]_1 = [\mathbf{A}_0]_1 \cdot \mathbf{r} \vee [\mathbf{x}]_1 = [\mathbf{A}_1]_1 \cdot \mathbf{r}\}$$

and $\text{par} := (\text{BG}, [\mathbf{A}_0]_1, [\mathbf{A}_1]_1)$ with $\text{BG} \leftarrow \text{BGGen}(1^\lambda)$ and $\mathbf{A}_0, \mathbf{A}_1 \xleftarrow{R} \mathcal{D}_{2k, k}$ for $k \in \mathbb{N}$. We henceforth denote our proof by **PS** and set $k = 1$ and consider the class of admissible transformations $\mathcal{T} := \{(T_x^\psi, T_w^\psi)\}_{\psi \in \mathbb{Z}_p^*}$ and $T_x^\psi([\mathbf{x}_1]_1, [\mathbf{x}_2]_1) := [\mathbf{x}_1]_1 + \psi[\mathbf{x}_2]_1$ and $T_w^\psi(r_1, r_2) := r_1 + \psi r_2$. Observe that the output of **ZKEval** is a proof with new randomness $v' = \alpha v$, $s'_0 = \alpha s_{1,0} + \alpha \psi s_{2,0} + \beta_0$ and $s'_1 = \alpha s_{1,1} + \alpha \psi s_{2,1} + \beta_1$ as well as new witness $r' = r_1 + \psi r_2$.

Below, we show that the protocol in Figure 2 is indeed a NIZK argument.

Theorem 1. *The protocol in Figure 2 is a malleable non-interactive zero-knowledge argument for the language $\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee$ with respect to allowable transformations \mathcal{T} .*

Proof. We need to prove three properties, perfect completeness, composable zero-knowledge, computational soundness and derivation privacy.

Completeness: This is easy to verify.

Zero-Knowledge: The challenger sends an MDDH challenge $([\mathbf{D}]_2, [\mathbf{z}]_2)$ to the adversary \mathcal{B} . Then \mathcal{B} picks $\mathbf{A}_0, \mathbf{A}_1 \xleftarrow{R} \mathcal{D}_{2,1}$, $\mathbf{A} \xleftarrow{R} \mathcal{D}_1$, $\mathbf{K} \xleftarrow{R} \mathbb{Z}_p^{2 \times 1}$ and computes $[\mathbf{P}]_2 = [\mathbf{z}^\top + \mathbf{D}^\top]_2 \mathbf{K}$ and $\mathbf{C} = \mathbf{K} \bar{\mathbf{A}}$.

<p>PGen(par, 1^λ) :</p> <hr/> <p>$\mathbf{D}, \mathbf{A} \xleftarrow{R} \mathcal{D}_1, \mathbf{z} \xleftarrow{R} \mathbb{Z}_p^2 \setminus \text{span}(\mathbf{D})$ $\mathbf{K} \xleftarrow{R} \mathbb{Z}_p^{2 \times 1}$ $\mathbf{M} := \mathbf{D} + \mathbf{z}$ $\mathbf{P} := \mathbf{M}^\top \mathbf{K}$ $\mathbf{C} := \mathbf{K} \overline{\mathbf{A}}$ crs = (par, $[\mathbf{D}]_2, [\mathbf{z}]_2, [\mathbf{P}]_2, [\overline{\mathbf{A}}]_1, [\mathbf{C}]_1$) return crs</p> <hr/> <p>PPro(crs, $[\mathbf{x}_1]_1, r_1, [\mathbf{x}_2]_1, r_2$) :</p> <hr/> <p>Let $b \in \{0, 1\}, j \in \{1, 2\}$ s.t. $[\mathbf{x}_j]_1 = [\mathbf{A}_b]_1 r_j$ $v \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{z}_{1-b}]_2 := v[\mathbf{D}]_2$ $[\mathbf{z}_b]_2 := v[\mathbf{z}]_2$ $\pi := v[\mathbf{P}]_2$</p> <p>$s_{1,0}, s_{1,1}, s_{2,0}, s_{2,1} \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{C}_{1,b}]_2 := s_{1,b}[\mathbf{D}]_2^\top + r_1[\mathbf{z}_b]_2$ $[\mathbf{\Pi}_{1,b}]_1 := [\mathbf{A}_b]_1^\top s_{1,b}$ $[\mathbf{C}_{1,1-b}]_2 := s_{1,1-b}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{1,1-b}]_1 := [\mathbf{A}_{1-b}]_1 \cdot s_{1,1-b} - [\mathbf{x}_1]_1 v$ $[\mathbf{C}_{2,b}]_2 := s_{2,b}[\mathbf{D}]_2^\top + r_2[\mathbf{z}_b]_2$ $[\mathbf{\Pi}_{2,b}]_1 := [\mathbf{A}_b]_1^\top s_{2,b}$ $[\mathbf{C}_{2,1-b}]_2 := s_{2,1-b}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{2,1-b}]_1 := [\mathbf{A}_{1-b}]_1 \cdot s_{2,1-b} - [\mathbf{x}_2]_1 v$ $\Omega := ([\mathbf{C}_{j,i}]_2, [\mathbf{\Pi}_{j,i}]_1, [\mathbf{z}_i]_2, \pi)_{j \in \{1,2\}, i \in \{0,1\}}$ return Ω</p> <hr/> <p>PVer(crs, $[\mathbf{x}_1]_1, [\mathbf{x}_2]_1, \Omega$) :</p> <hr/> <p>if $e([\overline{\mathbf{A}}]_1, \pi) = e([\mathbf{C}]_1, [\mathbf{z}_1]_2 + [\mathbf{z}_0]_2)$ and for all $i \in \{0, 1\}, j \in \{1, 2\}$ it holds $e([\mathbf{A}_i]_1, [\mathbf{C}_{j,i}]_2)$ $e([\mathbf{\Pi}_{j,i}]_1, [\mathbf{D}]_2^\top) + e([\mathbf{x}_j]_1, [\mathbf{z}_i]_2^\top)$ return 1 else return 0</p> <hr/> <p>PRVer(crs, $[\mathbf{x}'_1]_1, \Omega'_1$) :</p> <hr/> <p>if $e([\overline{\mathbf{A}}]_1, \pi') = e([\mathbf{C}]_1, [\mathbf{z}_1]_2 + [\mathbf{z}_0]_2)$ and for all $i \in \{0, 1\}$ it holds $e([\mathbf{A}_i]_1, [\mathbf{C}'_i]_2) =$ $e([\mathbf{\Pi}'_i]_1, [\mathbf{D}]_2^\top) + e([\mathbf{x}'_1]_1, [\mathbf{z}'_i]_2^\top)$ return 1 else return 0</p>	<p>PTGen(par, 1^λ) :</p> <hr/> <p>$\mathbf{D}, \mathbf{A} \xleftarrow{R} \mathcal{D}_1, u \xleftarrow{R} \mathbb{Z}_p$ $\mathbf{K} \xleftarrow{R} \mathbb{Z}_p^{2 \times 1}$ $\mathbf{z} := \mathbf{D}u$ $\mathbf{M} := \mathbf{D} + \mathbf{z}$ $\mathbf{P} := \mathbf{M}^\top \mathbf{K}$ $\mathbf{C} := \mathbf{K} \overline{\mathbf{A}}$ crs := (par, $[\mathbf{D}]_2, [\mathbf{z}]_2, [\mathbf{P}]_2, [\overline{\mathbf{A}}]_1, [\mathbf{C}]_1$) trap := ($u, \mathbf{K}$) return (crs, trap)</p> <hr/> <p>PSim(crs, trap, $[\mathbf{x}_1]_1, [\mathbf{x}_2]_1$) :</p> <hr/> <p>$v \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{z}_0]_2 := v[\mathbf{D}]_2$ $[\mathbf{z}_1]_2 := v[\mathbf{z}]_2$ $\pi := v[\mathbf{P}]_2$</p> <p>$s_{1,0}, s_{1,1}, s_{2,0}, s_{2,1} \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{C}_{1,0}]_2 := s_{1,0}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{1,0}]_1 := [\mathbf{A}_0]_1 s_{1,0} - [\mathbf{x}_1]_1 v$ $[\mathbf{C}_{1,1}]_2 := s_{1,1}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{1,1}]_1 := [\mathbf{A}_1]_1 \cdot s_{1,1} - [\mathbf{x}_1]_1 (vu)$ $[\mathbf{C}_{2,0}]_2 := s_{2,0}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{2,0}]_1 := [\mathbf{A}_0]_1 s_{2,0} - [\mathbf{x}_2]_1 v$ $[\mathbf{C}_{2,1}]_2 := s_{2,1}[\mathbf{D}]_2^\top$ $[\mathbf{\Pi}_{2,1}]_1 := [\mathbf{A}_1]_1 \cdot s_{2,1} - [\mathbf{x}_2]_1 (vu)$ $\Omega := ([\mathbf{C}_{j,i}]_2, [\mathbf{\Pi}_{j,i}]_1, [\mathbf{z}_i]_2, \pi)_{j \in \{1,2\}, i \in \{0,1\}}$ return Ω</p> <hr/> <p>ZKEval(crs, $[\mathbf{x}_1]_1, [\mathbf{x}_2]_1, \Omega$) :</p> <hr/> <p>Parse $\Omega = (\Omega_1, \Omega_2, [\mathbf{z}_i]_2, \pi)$ if PVer(crs, $[\mathbf{x}_1]_1, [\mathbf{x}_2]_1, \Omega$) = 0 return \perp</p> <p>else $\psi, \alpha, \beta_0, \beta_1 \xleftarrow{R} \mathbb{Z}_p^*$ and for all $b \in \{0, 1\}$ $[\mathbf{z}'_b]_2 := \alpha[\mathbf{z}_b]_2$ $[\mathbf{C}'_b]_2 := \alpha[\mathbf{C}_{1,b}]_2 + \alpha\psi[\mathbf{C}_{2,b}]_2 + \beta_b[\mathbf{D}]_2$ $[\mathbf{\Pi}'_b]_1 := \alpha[\mathbf{\Pi}_{1,b}]_1 + \alpha\psi[\mathbf{\Pi}_{2,b}]_1 + \beta_b[\mathbf{A}_b]_1$ $\pi' := \alpha\pi$ $\Omega' := (\Omega'_1, [\mathbf{z}'_i]_2, \pi')$ return Ω'</p>
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Fig. 2. Malleable NIZK argument for language $\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee$

Then \mathcal{B} sends $([\mathbf{A}_0]_1, [\mathbf{A}_1]_1, [\mathbf{z}]_2, [\mathbf{D}]_2, [\mathbf{P}]_2, [\overline{\mathbf{A}}]_1, [\mathbf{C}]_1)$ to \mathcal{A} as crs. When \mathcal{B} receives a real MDDH tuple, where $[\mathbf{z}]_2 = [\mathbf{D}u]_2$ for some $u \in \mathbb{Z}_p$, \mathcal{B} simulates crs as PTGen. In the other case, where $[\mathbf{z}]_2 \xleftarrow{R} \mathbb{G}_2^2$, using the fact that the uniform distribution over \mathbb{Z}_p^2 and the uniform distribution over $\mathbb{Z}_p^2 \setminus \text{span}(\mathbf{D})$ are $1/p$ -statistically close distributions, since \mathbf{D} is of rank 1, we can conclude that \mathcal{B} simulates the crs as output by PGen, within a $1/p$ statistical distance. Now, note that PPro and PSim compute the vectors $[\mathbf{z}_0]_2$ and $[\mathbf{z}_1]_2$ in the exact same way, i.e., for all $b \in \{0, 1\}$, $\mathbf{z}_b := \mathbf{D}v_b$ where v_0, v_1 are uniformly random over \mathbb{Z}_p subject to $v_1 = v_0u$ (recall $\mathbf{z} := \mathbf{D}u$).

Also for case $j = 1$, on input $[\mathbf{x}_1]_1 := [\mathbf{A}_b r_1]_1$, for some $b \in \{0, 1\}$, PPro(crs, $[\mathbf{x}_1]_1, [\mathbf{x}_2]_1, r_1, r_2$) computes $[\mathbf{C}_{1,1-b}]_2$ and $[\mathbf{II}_{1,1-b}]_1$ exactly as PSim, that is: $[\mathbf{C}_{1,1-b}]_2 = s_{1,1-b}[\mathbf{D}]_2$ and $[\mathbf{II}_{1,1-b}]_1 = [\mathbf{A}_{1-b}]_1 s_{1,1-b} - [\mathbf{x}_1]_1 v_{1-b}$. The algorithm PPro additionally computes $[\mathbf{C}_{1,b}]_2 = s_{1,b}[\mathbf{D}]_2 + r_1[\mathbf{z}]_2$ and $[\mathbf{II}_{1,b}]_1 = [\mathbf{A}_b]_1 s_{1,b}$, with $s_{1,b} \xleftarrow{R} \mathbb{Z}_p$. Since the following are identically distributed:

$$s_{1,b} \quad \text{and} \quad s_{1,b} - r_1 v_b$$

for $s_{1,b} \xleftarrow{R} \mathbb{Z}_p$, we can re-write the commitment and proof computed by PPro as $[\mathbf{C}_{1,b}]_2 = s_{1,b}[\mathbf{D}]_2 - r_1 v_b [\mathbf{D}]_2 + r_1 [\mathbf{z}_b]_2 = [s_{1,b} \mathbf{D}]_2$ and $[\mathbf{II}_{1,b}]_1 = [\mathbf{A}_b]_1 s_{1,b} - [\mathbf{A}_b r_1 v_b]_2 = [\mathbf{A}_b s_{1,b}]_1 - [\mathbf{x}_1 v_b]_2$, which is exactly as the output of PSim.

For case $j = 2$ the argumentation is analogous.

Computational Soundness: Based on the computational soundness of the QA-NIZK proofs [65], we have $\mathbf{z}_0 + \mathbf{z}_1 \notin \text{span}(\mathbf{D})$. So, there is a $b \in \{0, 1\}$ such that $\mathbf{z}_b \notin \text{span}(\mathbf{D})$. This implies that there exists a $\mathbf{d}^\perp \in \mathbb{Z}_p^2$ such that $\mathbf{D}^\top \mathbf{d}^\perp = 0$, and $\mathbf{z}_b^\top \mathbf{d}^\perp = 1$. Furthermore, as the row vectors of \mathbf{D} together with \mathbf{z}_b form a basis of \mathbb{Z}_p^2 , we can write $[\mathbf{C}_{j,b}]_2 := [s_{j,b} \mathbf{D} + r_j \mathbf{z}_b]_2$ for some $s_{j,b}, r_j \xleftarrow{R} \mathbb{Z}_p$. Multiplying the verification equation by \mathbf{d} thus yields $[\mathbf{A}_b r_j]_1 = [\mathbf{x}_j]_1$, which proves a successful forgery outside $\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee$ impossible.

Derivation privacy: As can be seen, the algorithm ZKEval outputs a proof with new independent randomness. So, the algorithm ZKEval and the algorithm PPro, when only compute a single proof, have identical distribution, i.e., we have perfect derivation privacy. More precisely, under the CRS $([\mathbf{A}_0]_1, [\mathbf{A}_1]_1, [\mathbf{z}]_2, [\mathbf{D}]_2, [\mathbf{P}]_2)$, a proof $\Omega' = (\Omega'_1, [\mathbf{z}'_i]_2, \pi')$ for word $[\mathbf{x}'_1]_1$ corresponding to witness r' has form $[\mathbf{z}'_{1-b}]_2 = v'[\mathbf{D}]_2$, $[\mathbf{z}'_b]_2 = v'[\mathbf{z}]_2$ and $\pi = v'[\mathbf{P}]_2$, and $[\mathbf{C}'_b]_2 = s'_b[\mathbf{D}]_2^\top + r'[\mathbf{z}'_b]_2$, $[\mathbf{\Pi}'_b]_1 = [\mathbf{A}_b]_1^\top s'_b$, $[\mathbf{C}'_{1-b}]_2 = s'_{1-b}[\mathbf{D}]_2^\top$ and $[\mathbf{\Pi}'_{1-b}]_1 = [\mathbf{A}_{1-b}]_1 \cdot s'_{1-b} - [\mathbf{x}'_1]_1 v'$ for new independent randomness r', v', s'_b, s'_{1-b} and so is a random element in the space of all proofs. Concluding, the proof output by ZKEval is distributed identically to a fresh proof output by PPro. \square

4.1 Our Core Lemma

We now give a new core lemma, which we denote by $\text{Exp}_\beta^{\text{core}}$. Note that we set $k = 1$, as it is sufficient for our construction of SPS-EQ. Consider following

$\text{Exp}_\beta^{\text{core}}(\lambda), \beta \in \{0, 1\} :$	$\text{TAGO}() :$
$\text{ctr} := 0$ $\text{BG} \leftarrow \text{BGGen}(1^\lambda)$ $\mathbf{A}_0, \mathbf{A}_1 \xleftarrow{R} \mathcal{D}_1$ $\text{par} := (\text{BG}, [\mathbf{A}_0]_1, [\mathbf{A}_1]_1)$ $\text{crs} \leftarrow \text{PGen}(\text{par}, 1^\lambda)$ $\mathbf{k}_0, \mathbf{k}_1 \xleftarrow{R} \mathbb{Z}_p^2$ $\text{pp} := (\text{BG}, [\mathbf{A}_0]_1, \text{crs})$ $\text{tag} \leftarrow \mathcal{A}^{\text{TAGO}}(\text{pp})$ return $\text{VERO}(\text{tag})$	$\text{ctr} := \text{ctr} + 1$ $r_1, r_2 \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{t}]_1 := [\mathbf{A}_0]_1 r_1, [\mathbf{w}]_1 := [\mathbf{A}_0]_1 r_2$ $\Omega := (\Omega_1, \Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi) \leftarrow \text{PPro}(\text{crs}, [\mathbf{t}]_1, r_1, [\mathbf{w}]_1, r_2)$ $[u']_1 := (\mathbf{k}_0 + \beta \cdot \mathbf{F}(\text{ctr}))^\top [\mathbf{t}]_1, [u'']_1 := (\mathbf{k}_0 + \beta \cdot \mathbf{k}_1)^\top [\mathbf{w}]_1$ $\text{Tag} := ([\mathbf{t}]_1, [\mathbf{w}]_1, \Omega = (\Omega_1, \Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi), [u']_1, [u'']_1)$ return Tag <hr/> $\text{VERO}(\text{tag}) :$ Parse $\text{tag} = ([\mathbf{t}]_1, \Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi, [u']_1)$ if $1 \leftarrow \text{PVer}(\text{crs}, [\mathbf{t}]_1, (\Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi))$ and $\exists \text{ctr}' \leq \text{ctr} : [u']_1 = (\mathbf{k}_0 + \beta \cdot \mathbf{F}(\text{ctr}'))^\top [\mathbf{t}]_1$ return 1 else return 0

experiments (for two cases $\beta = 0$ and $\beta = 1$), where $\mathbf{F} : \mathbb{Z}_p \rightarrow \mathbb{Z}_p^2$ is a random function computed on the fly:

Lemma 2 (Core lemma). *If the \mathcal{D}_1 -MDDH (DDH) assumption holds in \mathbb{G}_1 and the tuple of algorithms $(\text{PGen}, \text{PTGen}, \text{PPro}, \text{PVer})$ is a non-interactive zero-knowledge proof system for $\mathcal{L}_{\mathbf{A}_0, \mathbf{A}_1}^\vee$, then going from experiment $\text{Exp}_0^{\text{core}}$ to $\text{Exp}_1^{\text{core}}$ can (up to negligible terms) only increase the winning chance of an adversary. More precisely, for every adversary \mathcal{A} , there exist adversaries $\mathcal{B}, \mathcal{B}_1$ and \mathcal{B}_2 such that*

$$\text{Adv}_0^{\text{core}}(\mathcal{A}) - \text{Adv}_1^{\text{core}}(\mathcal{A}) \leq \Delta_{\mathcal{A}}^{\text{core}},$$

where

$$\begin{aligned} \Delta_{\mathcal{A}}^{\text{core}} = & (2 + 2\lceil \log Q \rceil) \text{Adv}_{\text{PS}}^{\text{zk}}(\mathcal{B}) + (8\lceil \log Q \rceil + 4) \text{Adv}_{\mathcal{D}_1, \mathbb{G}_s}^{\text{MDDH}}(\mathcal{B}_1) \\ & 2\lceil \log Q \rceil \text{Adv}_{\text{PS}}^{\text{snd}}(\mathcal{B}_2) + \lceil \log Q \rceil \Delta_{\mathcal{D}_1} + \frac{(8\lceil \log Q \rceil + 4)}{p-1} + \frac{(\lceil \log Q \rceil)Q}{p} \end{aligned}$$

and the term $\Delta_{\mathcal{D}_1}$ is statistically small.

Due to the lack of space and the similarity of the proof to the approach in [43] we present the full proof in the full version.

5 Our SPS-EQ Scheme

In Figure 3 we present our SPS-EQ scheme in the common parameter model under simple assumptions. We set $k = 1$ as we need randomizability and note that our scheme is based on the malleable OR-proof presented in Section 4. Observe that in ChgRep the new randomness is $v' = \alpha v$, $s'_0 = \alpha \mu s_{1,0} + \alpha \psi s_{2,0} + \beta_0$ and $s'_1 = \alpha \mu s_{1,1} + \alpha \psi s_{2,1} + \beta_1$ and the new witness is $r' = \mu r_1 + \psi r_2$.

<p>ParGen(1^λ) :</p> <hr/> <p>$\text{BG} \leftarrow \text{BGGen}(1^\kappa)$ $\mathbf{A}_0, \mathbf{A}_1 \xleftarrow{R} \mathcal{D}_1$ $\text{crs} \leftarrow \text{PGen}(\text{BG}, [\mathbf{A}_0]_1, [\mathbf{A}_1]_1, 1^\lambda)$ $\text{par} := (\text{BG}, [\mathbf{A}_0]_1, [\mathbf{A}_1]_1, \text{crs})$ return par</p> <hr/> <p>Sign($[\mathbf{m}]_1, \text{sk}$) :</p> <hr/> <p>$r_1, r_2 \xleftarrow{R} \mathbb{Z}_p$ $[\mathbf{t}]_1 := [\mathbf{A}_0]_1 r_1$ $[\mathbf{w}]_1 := [\mathbf{A}_0]_1 r_2$ $\Omega \leftarrow \text{PPro}(\text{crs}, [\mathbf{t}]_1, r_1, [\mathbf{w}]_1, r_2)$ $\Omega := (\Omega_1, \Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi)$ $\mathbf{u}_1 := \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{K}^\top [\mathbf{m}]_1$ $\mathbf{u}_2 := \mathbf{K}_0^\top [\mathbf{w}]_1$ $\sigma := ([\mathbf{u}_1]_1, \Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi, [\mathbf{t}]_1)$ $\tau := ([\mathbf{u}_2]_1, \Omega_2, [\mathbf{w}]_1)$ return (σ, τ)</p> <hr/> <p>Verify($[\mathbf{m}]_1, (\sigma, \tau), \text{pk}$) :</p> <hr/> <p>Parse $\sigma = ([\mathbf{u}_1]_1, \Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi, [\mathbf{t}]_1)$ Parse $\tau \in \{([\mathbf{u}_2]_1, \Omega_2, [\mathbf{w}]_1) \cup \perp\}$ 1: if $1 = \text{PVer}(\text{crs}, [\mathbf{t}]_1, (\Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi))$ 2: if $e([\mathbf{u}_1]_1^\top, [\mathbf{A}]_2) = e([\mathbf{t}]_1^\top, [\mathbf{K}_0 \mathbf{A}]_2) + e([\mathbf{m}]_1^\top, [\mathbf{K} \mathbf{A}]_2)$ if $\tau \neq \perp$ 3: if $1 \leftarrow \text{PVer}(\text{crs}, [\mathbf{w}]_1, (\Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi))$ $\Omega' := (\Omega'_1, [\mathbf{z}'_1]_2, \pi')$ 4: if $e([\mathbf{u}_2]_1^\top, [\mathbf{A}]_2) = e([\mathbf{w}]_1^\top, [\mathbf{K}_0 \mathbf{A}]_2)$ $\sigma' := ([\mathbf{u}'_1]_1, \Omega', [\mathbf{t}'_1]_1)$ return 1 return 1 else return 0</p>	<p>KeyGen(par, ℓ) :</p> <hr/> <p>$\mathbf{A} \xleftarrow{R} \mathcal{D}_1$ $\mathbf{K}_0 \xleftarrow{R} \mathbb{Z}_p^{2 \times 2}$ $\mathbf{K} \xleftarrow{R} \mathbb{Z}_p^{\ell \times 2}$ $\text{sk} := (\mathbf{K}_0, \mathbf{K})$ $\text{pk} := ([\mathbf{A}]_2, [\mathbf{K}_0 \mathbf{A}]_2, [\mathbf{K} \mathbf{A}]_2)$ return (pk, sk)</p> <hr/> <p>ChgRep($[\mathbf{m}]_1, \sigma, \tau, \mu, \text{pk}$) :</p> <hr/> <p>Parse $\sigma = ([\mathbf{u}_1]_1, \Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi, [\mathbf{t}]_1)$ Parse $\tau = ([\mathbf{u}_2]_1, \Omega_2, [\mathbf{w}]_1)$ $\Omega := (\Omega_1, \Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi)$ if $1 \neq \text{PVer}(\text{crs}, [\mathbf{t}]_1, [\mathbf{w}]_1, \Omega)$ or $e([\mathbf{u}_2]_1^\top, [\mathbf{A}]_2) \neq e([\mathbf{w}]_1^\top, [\mathbf{K}_0 \mathbf{A}]_2)$ or $e([\mathbf{u}_1]_1^\top, [\mathbf{A}]_2) \neq e([\mathbf{t}]_1^\top, [\mathbf{K}_0 \mathbf{A}]_2) + e([\mathbf{m}]_1^\top, [\mathbf{K} \mathbf{A}]_2)$ return \perp else $\psi, \alpha, \beta_0, \beta_1 \xleftarrow{R} \mathbb{Z}_p^*$ $[\mathbf{u}'_1]_1 := \mu[\mathbf{u}_1]_1 + \psi[\mathbf{u}_2]_1$ $[\mathbf{t}'_1]_1 := \mu[\mathbf{t}]_1 + \psi[\mathbf{w}]_1 = [\mathbf{A}_0]_1(\mu r_1 + \psi r_2)$ for all $b \in \{0, 1\}$ $[\mathbf{z}'_b]_2 := \alpha[\mathbf{z}_b]_2$ $[\mathbf{C}'_b]_2 := \alpha\mu[\mathbf{C}_{1,b}]_2 + \alpha\psi[\mathbf{C}_{2,b}]_2 + \beta_b[\mathbf{D}]_2$ $[\mathbf{\Pi}'_b]_1 := \alpha\mu[\mathbf{\Pi}_{1,b}]_1 + \alpha\psi[\mathbf{\Pi}_{2,b}]_1 + \beta_b[\mathbf{A}_b]_1$ $\pi' := \alpha\pi$ $\sigma' := ([\mathbf{u}'_1]_1, \Omega', [\mathbf{t}'_1]_1)$ return ($\mu[\mathbf{m}]_1, \sigma'$)</p>
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Fig. 3. Our SPS-EQ scheme.

Theorem 2. *If KerMDH and MDDH assumptions holds, our SPS scheme is unforgeable.*

Proof. We prove the claim by using a sequence of Games and we denote the advantage of the adversary in the j -th game as Adv_j .

Game 0: This game is the original game and we have:

$$\text{Adv}_0 = \text{Adv}_{\text{SPS-EQ}}^{\text{EUF-CMA}}(\mathcal{A})$$

Game 1: In this game, in **Verify**, we replace the verification in line (2:) with the following equation:

$$[\mathbf{u}_1^*]_1 = \mathbf{K}_0^\top [\mathbf{t}^*]_1 + \mathbf{K}^\top [\mathbf{m}^*]_1$$

For any signature $\sigma = ([\mathbf{u}_1^*]_1, \Omega_1^*, [\mathbf{z}_0^*]_2, [\mathbf{z}_1^*]_2, \pi^*, [\mathbf{t}^*]_1)$ that passes the original verification but not verification of Game 1 the value

$$[\mathbf{u}_1^*]_1 - \mathbf{K}_0^\top [\mathbf{t}^*]_1 - \mathbf{K}^\top [\mathbf{m}^*]_1$$

is a non-zero vector in the kernel of \mathbf{A} . Thus if \mathcal{A} outputs such a signature, we can construct an adversary \mathcal{B} that breaks the \mathcal{D}_1 -KerMDH assumption in \mathbb{G}_2 . To do this we proceed as follows: The adversary \mathcal{B} receives $(\text{BG}, [\mathbf{A}]_2)$, samples all other parameters and simulates Game 1 for \mathcal{A} . When \mathcal{B} receives the forgery from \mathcal{A} as tuple $\sigma = ([\mathbf{u}_1^*]_1, \Omega_1^*, [\mathbf{z}_0^*]_2, [\mathbf{z}_1^*]_2, \pi^*, [\mathbf{t}^*]_1)$ for message $[\mathbf{m}^*]_1$, he passes following values to its own challenger:

$$[\mathbf{u}_1^*]_1 - \mathbf{K}_0^\top [\mathbf{t}^*]_1 - \mathbf{K}^\top [\mathbf{m}^*]_1$$

We have:

$$|\text{Adv}_1 - \text{Adv}_0| \leq \text{Adv}_{\mathcal{D}_1, \mathbb{G}_2}^{\text{KerMDH}}(\mathcal{B})$$

Game 2: In this game, we set $\mathbf{K}_0 = \mathbf{K}_0 + \mathbf{k}_0(\mathbf{a}^\perp)^\top$ (in key generation we can pick $\mathbf{k}_0 \in \mathbb{Z}_p^2$ and $\mathbf{K}_0 \in \mathbb{Z}_p^{2 \times 2}$ and set \mathbf{K}_0 ; we have $\mathbf{a}^\perp \mathbf{A} = 0$). We compute $[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{K}^\top [\mathbf{m}]_1 + \mathbf{a}^\perp (\mathbf{k}_0)^\top [\mathbf{t}]_1$ and $[\mathbf{u}_2]_1 = \mathbf{K}_0^\top [\mathbf{w}]_1 + \mathbf{a}^\perp (\mathbf{k}_0)^\top [\mathbf{w}]_1$. There is no difference to the previous game since both are distributed identically. So, we have:

$$\text{Adv}_2 = \text{Adv}_1$$

Game 3: In this game, we add the part of $\mathbf{F}(\text{ctr})$ for $\text{ctr} = \text{ctr} + 1$, where \mathbf{F} is a random function, and obtain $[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{K}^\top [\mathbf{m}]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(\text{ctr}))^\top [\mathbf{t}]_1$ and $[\mathbf{u}_2]_1 = \mathbf{K}_0^\top [\mathbf{w}]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{k}')^\top [\mathbf{w}]_1$. In the verification we have:

$$1 \leftarrow \text{PVer}(\text{crs}, [\mathbf{t}]_1, (\Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi)) \quad \text{and}$$

$$\exists \text{ctr}' \leq \text{ctr} :$$

$$[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(\text{ctr}'))^\top [\mathbf{t}]_1 + \mathbf{K}^\top [\mathbf{m}]_1$$

Let \mathcal{A} be an adversary that distinguishes between Game 3 and Game 2. We can construct an adversary \mathcal{B}_1 that breaks the core lemma. \mathcal{B}_1 receives $\text{par} = (\text{BG}, [\mathbf{A}_0]_1, \text{crs})$ from $\text{Exp}_{\beta, \mathcal{B}_1}^{\text{core}}$. \mathcal{B}_1 picks $\mathbf{A} \xleftarrow{R} \mathcal{D}_k$, $\mathbf{a}^\perp \in \text{orth}(\mathbf{A})$, $\mathbf{K}_0 \xleftarrow{R} \mathbb{Z}_p^{2 \times 2}$, $\mathbf{K} \xleftarrow{R} \mathbb{Z}_p^{2 \times \ell}$, and sends public key $\text{pk} = ([\mathbf{A}_0]_1, [\mathbf{A}]_2, [\mathbf{K}_0 \mathbf{A}]_2, [\mathbf{K} \mathbf{A}]_2)$ to \mathcal{A} . \mathcal{B}_1 uses the oracle $\text{TAGO}()$ to construct the signing algorithm. This oracle takes no input and returns $\text{tag} = ([\mathbf{t}]_1, [\mathbf{w}]_1, \Omega = (\Omega_1, \Omega_2, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi), [u']_1, [u'']_1)$. Then \mathcal{B}_1 computes $[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{a}^\perp [u']_1 + \mathbf{K}^\top [\mathbf{m}]_1$, $[\mathbf{u}_2]_1 = \mathbf{K}_0^\top [\mathbf{w}]_1 + \mathbf{a}^\perp [u'']_1$, and sends the signature $\sigma = ([\mathbf{u}_1]_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi, [\mathbf{t}]_1)$ and tag $\tau = ([\mathbf{u}_2]_1, \Omega_2, [\mathbf{w}]_1)$ to \mathcal{A} . When the adversary \mathcal{A} sends his forgery $([\mathbf{m}^*]_1, \sigma^*) = (\mathbf{u}_1^*, [\mathbf{t}^*]_1, \Omega_1^*, [\mathbf{z}_0^*]_2, [\mathbf{z}_1^*]_2, \pi^*)$, \mathcal{B}_1 returns 0 if $[\mathbf{u}_1]_1 = 0$; otherwise he checks whether there exists $[u^*]_1$ such that $[\mathbf{u}_1^*]_1 - \mathbf{K}_0^\top [\mathbf{t}^*]_1 - \mathbf{K}^\top [\mathbf{m}^*]_1 = \mathbf{a}^\perp [u^*]_1$. If it does not hold, then it returns 0 to \mathcal{A} , otherwise \mathcal{B}_1 computes $[u^*]_1$, and calls

the verification oracle $\text{VERO}()$ on the tag $\text{tag}^* = ([\mathbf{t}^*]_1, \Omega_1^*, [\mathbf{z}_0^*]_2, [\mathbf{z}_1^*]_2, \pi^*, [u'^*]_1)$ and returns the answer to \mathcal{A} . Using the core lemma, we have:

$$\mathbf{Adv}_2 - \mathbf{Adv}_3 \leq \mathbf{Adv}_{\text{BG}}^{\text{core}}(\mathcal{B}_1)$$

Game 4: In this game, we pick r_1, r_2 from \mathbb{Z}_p^* instead of \mathbb{Z}_p . The difference of advantage between Game 3 and Game 4 is bounded by the statistical distance between the two distributions of r_1, r_2 . So, under Q adversarial queries, we have:

$$|\mathbf{Adv}_4 - \mathbf{Adv}_3| \leq \frac{Q}{p}$$

Game 5: In this game, we pick $\tilde{\text{ctr}} \xleftarrow{R} [1, Q]$, and we add a condition $\text{ctr}' = \tilde{\text{ctr}}$ to verification. Actually, now we have this conditions:

$$1 \leftarrow \text{PVer}(\text{pk}, [\mathbf{t}]_1, (\Omega_1, [\mathbf{z}_0]_2, [\mathbf{z}_1]_2, \pi)) \quad \text{and}$$

$$\exists \text{ctr}' \leq \text{ctr} : \text{ctr}' = \tilde{\text{ctr}} \quad \text{and}$$

$$[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(\text{ctr}'))^\top + \mathbf{K}^\top [\mathbf{m}]_1$$

Since the view of the adversary is independent of $\tilde{\text{ctr}}$, we have

$$\mathbf{Adv}_5 = \frac{\mathbf{Adv}_4}{Q}$$

Game 6: In this game, we can replace \mathbf{K} by $\mathbf{K} + \mathbf{v}(\mathbf{a}^\perp)^\top$ for $\mathbf{v} \xleftarrow{R} \mathbb{Z}_p^\ell$. Also, we replace $\{\mathbf{F}(i) : i \in [1, Q], i \neq \tilde{\text{ctr}}\}$ by $\{\mathbf{F}(i) + \mathbf{w}_i : i \in [1, Q], i \neq \tilde{\text{ctr}}\}$, for $\mathbf{w}_i \xleftarrow{R} \mathbb{Z}_p^{2k}$ and $i \neq \tilde{\text{ctr}}$. So, in each i -th query, where $i \neq \tilde{\text{ctr}}$, we compute

$$[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + (\mathbf{K}^\top + \mathbf{a}^\perp \mathbf{v}^\top) [\mathbf{m}_i]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(i) + \mathbf{w}_i)^\top [\mathbf{t}]_1$$

Also, for $\tilde{\text{ctr}}$ -th query for the message $[\mathbf{m}_{\tilde{\text{ctr}}}]_1$, we compute

$$[\mathbf{u}_1]_1 = \mathbf{K}_0^\top [\mathbf{t}]_1 + (\mathbf{K}^\top + \mathbf{a}^\perp \mathbf{v}^\top) [\mathbf{m}_{\tilde{\text{ctr}}}]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(\tilde{\text{ctr}}) + \mathbf{w}_i)^\top [\mathbf{t}]_1$$

So, \mathcal{A} must compute the following:

$$[\mathbf{u}_1^*]_1 = \mathbf{K}_0^\top [\mathbf{t}^*]_1 + (\mathbf{K}^\top + \mathbf{a}^\perp \mathbf{v}^\top) [\mathbf{m}^*]_1 + \mathbf{a}^\perp (\mathbf{k}_0 + \mathbf{F}(\tilde{\text{ctr}}) + \mathbf{w}_i)^\top [\mathbf{t}^*]_1$$

Since $\mathbf{m}^* \neq [\mathbf{m}_{\tilde{\text{ctr}}}]_{\mathcal{R}}$ (in different classes) by definition of the security game, we can argue $\mathbf{v}^\top \mathbf{m}^*$ and $\mathbf{v}^\top \mathbf{m}_{\tilde{\text{ctr}}}$ are two independent values, uniformly random over \mathbb{G}_1 . So, \mathcal{A} only can guess it with probability of $\frac{1}{p}$. So, we have

$$\mathbf{Adv}_{\text{SPS-EQ}}^{\text{EUF-CMA}}(\mathcal{A}) \leq \mathbf{Adv}_{\text{BG}}^{\text{KerMDH}}(\mathcal{B}) + \mathbf{Adv}_{\text{BG}}^{\text{core}}(\mathcal{B}_1) + \frac{2Q}{p}.$$

Theorem 3. *Our scheme satisfies perfect adaption under malicious keys in the honest parameters model, i.e., Definition 10.*

Proof. For any message $[\mathbf{m}]_1$, and \mathbf{pk} which is generated according to the CRS $([\mathbf{A}]_2, [\mathbf{A}_0]_1, [\mathbf{A}_1]_1, [\mathbf{z}]_2, [\mathbf{D}]_2, [\mathbf{P}]_2)$, a signature $\sigma = ([\mathbf{u}]_1, \Omega, [\mathbf{t}]_1)$ satisfying the verification algorithm must be of the form $\sigma = (\mathbf{K}_0^\top [\mathbf{A}_0]_1 r + \mathbf{K}^\top [\mathbf{m}]_1, v[\mathbf{z}]_2, v[\mathbf{D}]_2, v[\mathbf{P}]_2, s_0[\mathbf{D}^\top] + rv[\mathbf{z}]_2, s_1[\mathbf{D}^\top]_2, [\mathbf{A}_0]_1 s_0, [\mathbf{A}_1]_1 s_1 - [\mathbf{A}_0]_1 r v, [\mathbf{A}_0]_1 r)$. A signature output by `ChgRep` has the form $\sigma' = (\mathbf{K}_0^\top [\mathbf{A}_0]_1 r' + \mathbf{K}^\top [\mathbf{m}]_1, v'[\mathbf{z}]_2, v'[\mathbf{D}]_2, v'[\mathbf{P}]_2, s'_0[\mathbf{D}^\top] + r'v'[\mathbf{z}]_2, s'_1[\mathbf{D}^\top]_2, [\mathbf{A}_0]_1 s'_0, [\mathbf{A}_1]_1 s'_1 - [\mathbf{A}_0]_1 r' v', [\mathbf{A}_0]_1 r')$ for new independent randomness r', v', s'_0, s'_1 and so is a random element in the space of all signatures. Actually, the signature output by `ChgRep` is distributed identically to a fresh signature on message $[\mathbf{m}]_1$ output by `Sign`. \square

6 Applications

As already discussed in [35], there are no known applications of SPS-EQ where signatures that have been randomized need to be randomized again by an entity that does not know the original signature. Consequently, and as shown in [35], tag-based schemes as the one introduced in this paper can be used within all the known applications without restrictions. Now let us summarize and clarify how our SPS-EQ scheme can be used in existing applications of SPS-EQ.

Using our scheme we can instantiate the group signatures in [30] and [11] as well as access control encryption (ACE) in [36]. As already mentioned earlier, both models assume honest key generation and so we can merge `ParGen` and `KeyGen` of the SPS-EQ scheme and do not need a trusted party to generate the CRS, i.e., it can be done by the signer during key generation.

Also we can instantiate attribute-based credentials [52, 38, 40] in the honest key model or under malicious keys (for latter requiring a CRS), but not in the malicious key model without a CRS. Due to an argumentation following a reasoning related to the one in Section 3.3, our scheme cannot be used to instantiate the verifiable encrypted signatures from [51].

Round-optimal blind signatures in the CRS model. What remains to be discussed is the application to round-optimal blind signatures as introduced in [39, 37]. As already mentioned, as our SPS-EQ scheme does not provide the strongest notion of perfect adaption under malicious keys, we are only able to construct round-optimal blind signatures in the CRS model. In contrast to existing schemes in the CRS model relying on non-standard and non-static q -type assumptions such as [33, 9] which require around 30 group elements in the signature, the most recent scheme under standard assumptions, i.e., SXDH, by Abe et al. [8] requires (42, 40) elements in \mathbb{G}_1 and \mathbb{G}_2 respectively. In contrast to other existing schemes which follow the framework of Fischlin [32], we can take our SPS-EQ scheme to instantiate the framework in [39]. We note that when we are in the CRS model, we can move the commitment parameters Q and \hat{Q} from [39] in the CRS, and thus obtain a round optimal blind signature scheme under SXDH. This is the same assumption as used by Abe et al. in [8], but our signature sizes are only (10, 9) elements in \mathbb{G}_1 and \mathbb{G}_2 respectively, improving over [8] by about a factor of 4 and even beating constructions proven secure

under q -type assumptions.

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