Short Identity-Based Signatures with Tight Security from Lattices

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Abstract. We construct a short and adaptively secure identity-based signature scheme *tightly* based on the well-known Short Integer Solution (SIS) assumption. Although identity-based signature schemes can be tightly constructed from either standard signature schemes against adaptive corruptions in the multi-user setting or a two-level hierarchical identity-based encryption scheme, neither of them is known with short signature size and tight security based on the SIS assumption. Here "short" means the signature size is independent of the message length, which is in contrast to the tree-based (tight) signatures.

Our approach consists of two steps: Firstly, we give two generic transformations (one with random oracles and the other without) from non-adaptively secure identity-based signature schemes to adaptively secure ones tightly. Our idea extends the similar transformation for digital signature schemes. Secondly, we propose two constructions of non-adaptively secure identity-based signature scheme based on the SIS and Ring-SIS assumptions in the random oracle model.

Keywords. Identity-based Signatures, Tight Security, (Ring) Short Integer Solution Assumption, Lattices.

1 Introduction

Tight Security. In public-key cryptography, we often prove the security of a scheme by reductions. Namely, we prove that, if there is an adversary $\mathcal{A}$ that can break the security of a scheme, then we can construct a reduction $\mathcal{R}$ to solve some hard problem (for instance, the short integer solution (SIS) problem [2]). More precisely, by doing this, we establish the relation that $\varepsilon_{\mathcal{A}} \leq \ell \cdot \varepsilon_{\mathcal{R}}$ and the running time of $\mathcal{A}$ and $\mathcal{R}$ are roughly the same, where $\varepsilon_{\mathcal{A}}$ and $\varepsilon_{\mathcal{R}}$ are the success probability of $\mathcal{A}$ and $\mathcal{R}$, respectively.

In particular, if the security loss ℓ is a small constant, then we call the reduction *tight* [5,7]. Recently, a relaxed notion called "almost tight" is considered [13,23], where the security loss can be dependent linearly or logarithmically on the

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security parameter. A cryptographic scheme with tight reductions does not need to increase the key length to compensate a security loss.

In the recent years, many tools have been developed to construct tightly secure cryptosystems [31,30,22,23,13,9,37]. However, currently, many of these techniques crucially require pairing groups and the Diffie-Hellman assumption which is known to be insure against a powerful quantum computer. The digital signature scheme in [1,8] and the identity-based encryption schemes in [11,33] are among the few exceptions which have tight post-quantum security using lattice-based techniques.

Our goal: Identity-based signatures with tight post-quantum security. We are interested in advanced cryptographic schemes with tight post-quantum security. In this paper, we consider identity-based signature (IBS) schemes [51]. In an IBS, an honest user with identity id can sign a message m using its secret key $\mathsf{sk}_{\mathsf{id}}$, and a signature σ can be publicly verified, given the master public key mpk and a user's identity id. We are interested in the adaptive security of IBS schemes, where an adversary aims at forging a fresh signature after adaptively learning users' secret keys and signatures. The use of identity-based cryptography can simplify the PKI requirements, and we refer [34] for more discussion about that.

There are mainly two approaches to construct IBS schemes, but neither of them directly yields an IBS scheme with tight post-quantum security. The first approach [17,6] is to transform a (standard) signature scheme into an IBS, which is often referred as the certification approach. The generic transformations in [17,6] are not tight. Recently, it has been shown that, if the underlying signature scheme is tightly secure in the multi-user setting with adaptive corruption, then the IBS scheme is tightly secure [40].

Compared to the classical unforgeability in the single-user setting (EUF-CMA) [29], the multi-user security with corruption (MU-EUF-CMA^{corr}) [3] is a stronger security notion for signature schemes, where an adversary receives verification keys of multiple users and is allowed corrupt some of them. Although EUF-CMA non-tightly implies MU-EUF-CMA^{corr}, constructing a tightly MU-EUF-CMA^{corr} secure signature scheme is highly challenging: To the best of our knowledge, [27,3,16] are the only schemes that have tight MU-EUF-CMA^{corr} security, and they are all based on the Diffie-Hellman assumption. There is a generic construction in [3], but it requires a non-interactive witness-indistinguishable proof of knowledge (NIWIPoK) system. It is unclear how to efficiently construct this particular proof system and to instantiate their generic construction in the post-quantum setting.

To give a bit more technical insights to it, in the lattice setting, one may consider to use a proof system (for instance, the one in [15]) together with the OR-proof technique [14] to construct such a NIWIPoK system. However, it requires the rewinding technique to show the PoK property, which leads to a non-tight reduction. Alternatively, one can directly use the Unruh proof system [52] that has tight NIWIPoK, but its proof size is linear in the security parameter, which is insufficient for a short IBS scheme.

The second approach [34] is to transform a 2-level hierarchical IBE (HIBE) [26] tightly to an IBS scheme. However, the existing tightly secure HIBE schemes are pairing-based [37,38,39]. We note that in [11] Boyen and Li proposed an almost tightly secure lattice-based IBE and claimed (without a concrete scheme) that it can be turned into a 2-level HIBE. Their construction is motivated by the Katz-Wang "random-bit" technique [28], and it is rather inefficient, due to the use of lattice-based PRFs and their homomorphic evaluation. Lattice-based PRFs [4,32,35] often use a large modulus and have almost tightness only. In Section 1.2, we further sketch why the "random-bit" technique is not enough for achieving our goal.

Our results. We propose the *first* tightly secure IBS scheme based on lattices. We prove the tight adaptive security of our IBS scheme based on the short integer solution (SIS) [2] and Ring-SIS [44] assumptions which are quantum-safe. Our Ring-SIS-based construction offers better efficiency due to shorter public keys. Our proofs are in the random oracle model. Different to the tree-based tight SIS-based signature scheme in [8], our signatures are short and contain only constant number of elements. Our scheme uses the Micciancio-Peikert (MP) trapdoor technique [46] and the Bonsai tree technique [12]. Moreover, our construction does not require any lattice-based PRF as in [11].

1.1 Technical Details

We achieve our results in two steps.

Step 1: IBS with non-adaptive security. We consider a (weaker) non-adaptive security of IBS schemes, where an adversary has to commit its user secret key queries and signing queries before receiving the master public key. This weaker security gives rise to a tight construction. The main reason is that in the security proof, since adversaries' user secret key queries and signing queries are committed in advance, the reduction can tightly embed the SIS instances in the forgery without any guessing.

More precisely, the overall idea of our non-adaptively secure scheme is as follows. The master public key of our scheme is a random matrix $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ with $m \geq 3n \log q$ where the SIS assumption holds, and the master secret key is a MP trapdoor [46] for $\mathbf{A}$. For generating user secret keys and signing, we associate matrices $\mathbf{F}_{\mathsf{id}} := [\mathbf{A} \mid \mathsf{H}_1(\mathsf{id})] \in \mathbb{Z}_q^{n\times(m+n\lceil\log q\rceil)}$ and $\mathbf{F}_{\mathsf{id},\mathsf{m}} := [\mathbf{A} \mid \mathsf{H}_1(\mathsf{id}) \mid \mathsf{H}_2(\mathsf{id},\mathsf{m})] \in \mathbb{Z}_q^{n\times(m+2n\lceil\log q\rceil)}$ with identity id and message m, where $\mathsf{H}_1, \mathsf{H}_2 : \{0,1\}^* \to \mathbb{Z}_q^{n\times n\lceil\log q\rceil}$ will be simulated as random oracles in the security proof. The secret key of identity id is a MP trapdoor for $\mathbf{F}_{\mathsf{id}}$. Given the trapdoor of $\mathbf{A}$, this can be efficiently computed using trapdoor delegation, e.g. the Bonsai technique [12]. The signature for message m under identity id is a "short" integer vector $\mathbf{z}$ in the kernel of $\mathbf{F}_{\mathsf{id},\mathsf{m}}$ (namely, $\mathbf{F}_{\mathsf{id},\mathsf{m}} \cdot \mathbf{z} = \mathbf{0}$).

Now we are ready to sketch our tight proof. We denote the list of all identities id for user secret key queries as $\mathcal{L}_{id}$, and the list of all identity-message pairs $(\mathsf{id}, \mathsf{m})$ for signing queries as $\mathcal{L}_m$. An adversary $\mathcal{A}$ has to output these two lists before receiving the master public key. The key step in our proof is that, by

programming the random oracles H_1 and H_2, the reduction can embed a gadget matrix into $\mathbf{F}_{\mathsf{id}}$ (for all $\mathsf{id} \in \mathcal{L}_{id}$) and $\mathbf{F}_{\mathsf{id},\mathsf{m}}$ (for all $(\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$) so that efficiently inverting the SIS function for these $\mathbf{F}_{\mathsf{id}}$ and $\mathbf{F}_{\mathsf{id},\mathsf{m}}$ is possible. However, for all $\mathsf{id}^* \notin \mathcal{L}_{id}$ and $(\mathsf{id}^*, \mathsf{m}^*) \notin \mathcal{L}_m$, $\mathbf{F}_{\mathsf{id}^*}$ and $\mathbf{F}_{\mathsf{id}^*,\mathsf{m}^*}$ are random matrices and inverting the SIS function for these random matrices is hard. Here, the reduction does not need to guess the forgery $(\mathsf{id}^*, \mathsf{m}^*)$, and thus it is tight.

Step 2: From non-adaptive to adaptive security. For digital signature schemes, it is known that, using a chameleon hash, the non-adaptive security can be tightly transformed to adaptive security [36]. This transformation has been used in the lattice-setting as well [12,46] with the SIS-based chameleon hash function [12]. We note that there is a Ring-SIS-based chameleon hash function in [19]. In this paper, we extend this generic transformation to the IBS setting, and thus our tightly non-adaptively secure IBS yields a tight scheme with adaptive security. Moreover, we propose a more efficient transformation in the random oracle model (cf. Section 3.2), since our non-adaptively secure scheme uses random oracles already. The common practice of instantiating the random oracle with a hash function such as SHA3 will be more efficient than using the chameleon hash technique. In particular, signature sizes are roughly the same, whereas the chameleon hash based on SIS requires to add a matrix to the public key. Further, the computation of this chameleon hash function is less efficient than an highly optimized evaluation of SHA3.

Extension and future work. We note that our approach can be naturally extended to hierarchical IBS schemes. We leave this as a future work. We also leave constructing an efficient non-adaptively secure short IBS with tight security in the standard model as an open problem. In combination with our transformation from Section 3, this will lead to an adaptively secure short IBS in the standard model with tight security.

1.2 More on Related Work

The Katz-Wang "random-bit" technique. The "random-bit" technique can be used to turn the non-tight Gentry-Peikert-Vaikuntanathan (GPV) IBE [25] to a tightly secure one [11,33]. However, we suppose this technique is not useful to construct a tightly secure 2-level HIBE. The high-level idea can be sketched easily. In the tight IBE, the secret key of identity id can be viewed as the GPV secret key of identity $(\mathsf{id}, b_{\mathsf{id}})$, where $b_{\mathsf{id}} \in \{0, 1\}$ is a random bit associated with id, and the ciphertext of m under id^* contains two GPV ciphertexts $(\mathsf{c}_0, \mathsf{c}_1)$ of m under identity $(\mathsf{id}^*, 0)$ and $(\mathsf{id}^*, 1)$. In the security proof, by putting a lattice trapdoor in the b_{id}-side and embedding an LWE instance in $(1 - b_{\mathsf{id}})$-side for all identities id, we generate secret keys for identities $(\mathsf{id}, b_{\mathsf{id}})$ and randomize $\mathsf{c}_{1-b_{\mathsf{id}^*}}$ in the challenge ciphertext. This is the key step, and it is important that b_{id^*} to be perfectly hidden, as otherwise the adversary may attack the side without any LWE instance.

One can extend this "random-bit" idea to the 2-level HIBE in the natural manner, namely, the secret key of identity $(\mathsf{id}_1, \mathsf{id}_2)$ is the secret key of identity $(\mathsf{id}_1, b_{\mathsf{id}_1}, \mathsf{id}_2, b_{\mathsf{id}_2})$ in the 2-level GPV HIBE. The encryption algorithm is adapted accordingly. Imagine that $(\mathsf{id}_1^*, \mathsf{id}_2^*)$ is the challenge identity for the 2-level HIBE. An adversary can learn the bit $b_{\mathsf{id}_1^*}$ used by the reduction, by asking a user secret key of $(\mathsf{id}_1^*, \mathsf{id}_2)$ with $\mathsf{id}_2 \neq \mathsf{id}_2^*$. The similar problem will happen, when we directly use this technique in constructing tightly secure IBS. Thus, we believe the Katz-Wang "random-bit" technique is not useful in constructing tightly secure 2-level HIBE or IBS.

Other tightly secure IBS. We note that in [54] a tightly secure IBS scheme is proposed in a weaker security model, where an adversary cannot ask for the secret key of id if a signature has been asked for id. Moreover, their security relies on the factoring-based and Dlog-based assumptions, while ours is based on the quantum-safe (Ring-)SIS assumption.

Comparison with the Certification Approach. Finally, we compare the efficiency of our scheme with those obtained via the certification approach in Table 1. Here we only focus on instantiating this approach with digital signature schemes based on the plain SIS assumption in the random oracle model, namely, [25,41] and our instantiation from SIS.

Scheme	tight	$\lvert\mathsf{mpk}\rvert$	$\lvert\sigma\rvert$
Section 4 + Section 3.1	✓	$2M$	$(3m + 2n \log q)z$
Section 4 + Section 3.2	✓	M	$(m + 2n \log q)z + 2\omega(\log \lambda)$
GPV [25] + Cert.	✗	M	$M + 2mz$
Lyu [41] + Cert.	✗	$M + n^2 z$	$M + (n^2 + 2m)z + 2\omega(\log \lambda)$

Table 1. Comparison of our results with identity-based signature schemes obtained by applying the certification approach [34]. We use the chameleon hash function given in [12]. All sizes are in bits, where M denotes the size of an SIS matrix and z the size of an element in $\mathbb{Z}_q$.

We note that the certification approach increases the size of user secret keys and signatures. Namely, a user secret key consists of a secret key, a public key and a signature of the underlying signature scheme, and an identity-based signature contains a public key and two signatures. For schemes in [25,41], their public keys contain a matrix. This is the reason why their signature size (in terms of numbers of elements) is quadratic in n, while ours is linear. For schemes based on structured assumptions such as Dilithium [18] and Falcon [21], the certification method will lead to a linear overhead which is comparable to our instantiation based on Ring-SIS, but our scheme is tightly secure.

2 Preliminaries

We use standard notation for sets $\mathbb{N}, \mathbb{P}, \mathbb{R}, \mathbb{Z}, \mathbb{Z}_q$ of natural numbers, primes, real numbers, integers and integers modulo $q \in \mathbb{N}$, respectively. By $[n] := \{1, \ldots, n\}$ we denote the set of the first n natural numbers. We denote the security parameter by $\lambda \in \mathbb{N}$. All algorithms will get 1^λ either explicitly or implicitly as an input. A probabilistic algorithm $\mathcal{A}$ is said to be PPT (probabilistic polynomial time) if its running time can be bounded by a polynomial in its input size. We also make use of standard asymptotic notation for positive functions such as ω and O. A function $\nu : \mathbb{N} \to \mathbb{R}$ is negligible in its input λ if $\nu \in \lambda^{-\omega(1)}$. The term $\mathsf{negl}(\lambda)$ always denotes a negligible function. If a function ν is at least $1 - \mathsf{negl}(\lambda)$, we say that it is overwhelming.

Matrices and vectors are written in bold letters. Vectors should be understood as column vectors. The Euclidean norm of a vector $\mathbf{v}$ is denoted by $\|v\|$, and the spectral norm of a matrix $\mathbf{A}$ is denoted by $s_1(\mathbf{A})$.

If $\mathcal{D}$ is a distribution, we write $x \leftarrow \mathcal{D}$ to state that x is sampled from $\mathcal{D}$. If S is a finite set, the notation $x \xleftarrow{\$} S$ states that x is sampled uniformly random from S. The statistical distance of distributions $\mathcal{D}_1, \mathcal{D}_2$ on the support $\mathcal{X}$ is defined to be $\frac{1}{2}\sum_{x \in \mathcal{X}} |\Pr[\mathcal{D}_1 = x] - \Pr[\mathcal{D}_2 = x]|$. If the statistical distance is negligible in λ, we say the distributions are statistically close. The min-entropy is $H_\infty(\mathcal{D}_1) := -\log(\max_{x \in \mathcal{X}} \Pr[\mathcal{D}_1 = x])$.

If A is an algorithm, the notation $y \leftarrow \mathsf{A}(x)$ means that the variable y is assigned to the output of A on input x. Sometimes we make the randomness used by an algorithm explicit by writing $y = \mathsf{A}(x; r)$ if $r \in \{0,1\}^*$ is $\mathsf{A}'s$ randomness. If we want to state that y is a possible output of A on input x, we write $y \in \mathsf{A}(x)$. We use the notation $\mathbf{T}(\mathsf{A})$ for running time. In all code-based security games, numerical values are assumed to be implicitly initialized as 0, sets and lists as $\emptyset$. If $\mathbf{G}$ is a game, we write $\mathbf{G}^{\mathcal{A}}_{\Pi}(1^\lambda) \Rightarrow b$ to state that the game $\mathbf{G}$ outputs the bit $b \in \{0,1\}$ considering the adversary $\mathcal{A}$ and the scheme Π.

Definition 1 (Chameleon Hash Function). *A $\varepsilon_{\mathsf{trap}}$-chameleon hash function (CHF) is a triple of PPT algorithms $\mathsf{CHF} = (\mathsf{CHGen}, \mathsf{CHash}, \mathsf{CHColl})$, where*

- $\mathsf{CHGen}(1^\lambda)$ *takes as input the security parameter 1^λ and outputs the hash key hk and the trapdoor td. We assume that hk implicitly defines a message space $\mathcal{M}_{\mathsf{hk}}$, a randomness distribution $\mathcal{R}_{\mathsf{hk}}$ and hash value space $\mathcal{H}_{\mathsf{hk}}$.*
- $\mathsf{CHash}(\mathsf{hk}, \mathsf{m}; r)$ *takes as input the hash key hk, a message $\mathsf{m} \in \mathcal{M}_{\mathsf{hk}}$ and randomness $r \in \mathcal{R}_{\mathsf{hk}}$ and outputs a hash value $h \in \mathcal{H}_{\mathsf{hk}}$.*
- $\mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, \mathsf{m}, r, \hat{\mathsf{m}})$ *takes as input the hash key hk, a message $\mathsf{m} \in \mathcal{M}_{\mathsf{hk}}$, randomness $r \in \mathcal{R}_{\mathsf{hk}}$ and a message $\hat{\mathsf{m}}$ and outputs a value $\hat{r} \in \mathcal{R}_{\mathsf{hk}}$.*
- *For every $(\mathsf{hk}, \mathsf{td}) \in \mathsf{CHGen}(1^\lambda)$, $\mathsf{m}, \mathsf{m}' \in \mathcal{M}_{\mathsf{hk}}$ the following distributions have statistical distance at most $\varepsilon_{\mathsf{trap}}$:*

$$\left\{ (r, h) \middle| \begin{array}{c} r \leftarrow \mathcal{R}_{\mathsf{hk}}, \\ h := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}; r) \end{array} \right\} \text{ and } \left\{ (r, h) \middle| \begin{array}{c} r' \leftarrow \mathcal{R}_{\mathsf{hk}}, h := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}'; r'), \\ r \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, \mathsf{m}', r', \mathsf{m}) \end{array} \right\}.$$

If $\varepsilon_{\mathsf{trap}}$ is negligible in λ, we simply say that CHF is a chameleon hash function.

Definition 2 (Collision Resistant CHF). *Let* $\mathsf{CHF} = (\mathsf{CHGen}, \mathsf{CHash}, \mathsf{CHColl})$ *be a chameleon hash function. We say that* CHF *is collision resistant if for every* PPT *algorithm* $\mathcal{A}$ *the following advantage is negligible in* λ*:*

$$\mathsf{Adv}^{\mathsf{coll}}_{\mathcal{A},\mathsf{CHF}}(\lambda) := \Pr\left[\begin{array}{c}\mathsf{CHash}(\mathsf{hk},\mathsf{m};r) = \mathsf{CHash}(\mathsf{hk},\mathsf{m}';r') \\ \wedge(\mathsf{m},r) \neq (\mathsf{m}',r')\end{array}\middle|\begin{array}{l}(\mathsf{hk},\mathsf{td}) \leftarrow \mathsf{CHGen}(1^\lambda) \\ (\mathsf{m},r,\mathsf{m}',r') \leftarrow \mathcal{A}(\mathsf{hk})\end{array}\right].$$

We note that chameleon hash functions based on lattice assumptions are known in the literature [12].

Definition 3 (Identity-Based Signature Scheme). *An Identity-based Signature Scheme (IBS) is defined as a tuple of* PPT *algorithms* $\mathsf{IBS} = (\mathsf{Setup}, \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$*, where*

- $\mathsf{Setup}(1^\lambda)$ *takes as input the security parameter* 1^λ *and outputs a master public key* mpk *and a master secret key* msk*. We assume that* mpk *implicitly defines a message space* $\mathcal{M} = \mathcal{M}_{\mathsf{mpk}}$ *and an identity space* $\mathcal{ID} = \mathcal{ID}_{\mathsf{mpk}}$*.*
- $\mathsf{KeyExt}(\mathsf{msk},\mathsf{id})$ *takes as input a master secret key* msk *and an identity* $\mathsf{id} \in \mathcal{ID}$ *and outputs a secret key* $\mathsf{sk}_{\mathsf{id}}$*, we assume that* $\mathsf{sk}_{\mathsf{id}}$ *implicitly contains* id*.*
- $\mathsf{Sig}(\mathsf{sk}_{\mathsf{id}},\mathsf{m})$ *takes as input a secret key* $\mathsf{sk}_{\mathsf{id}}$ *and a message* $\mathsf{m} \in \mathcal{M}$ *and outputs a signature* σ*.*
- $\mathsf{Ver}(\mathsf{mpk},\mathsf{id},\mathsf{m},\sigma)$ *is deterministic, takes as input a master public key* mpk*, identity* $\mathsf{id} \in \mathcal{ID}$*, message* $\mathsf{m} \in \mathcal{M}$ *and signature* σ *and outputs a bit* $b \in \{0,1\}$*.*

We say that IBS *is* ρ*-complete, if for every* $(\mathsf{mpk},\mathsf{msk}) \in \mathsf{Setup}(1^\lambda), \mathsf{m} \in \mathcal{M}, \mathsf{id} \in \mathcal{ID}$ *we have*

$$\Pr\left[\mathsf{Ver}(\mathsf{mpk},\mathsf{id},\mathsf{m},\sigma) = 1 \mid \mathsf{sk}_{\mathsf{id}} \leftarrow \mathsf{KeyExt}(\mathsf{msk},\mathsf{id}), \sigma \leftarrow \mathsf{Sig}(\mathsf{sk}_{\mathsf{id}},\mathsf{m})\right] \geq \rho.$$

Definition 4 (Security of IBS). *Let* $\mathsf{IBS} = (\mathsf{Setup}, \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$ *be an IBS and consider games* $\mathbf{UF\text{-}CMA}, \mathbf{UF\text{-}naCMA}$ *given in Fig. 1. We say that* IBS *is* $\mathsf{UF\text{-}naCMA}$ *secure, if for every* PPT *adversary* $\mathcal{A}$ *the following advantage is negligible in* λ*:*

$$\mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{A},\mathsf{IBS}}(\lambda) := \Pr\left[\mathbf{UF\text{-}naCMA}^{\mathcal{A}}_{\mathsf{IBS}}(\lambda) \Rightarrow 1\right].$$

We say that IBS *is* $\mathsf{UF\text{-}CMA}$ *secure, if for every* PPT *adversary* $\mathcal{A}$ *the following advantage is negligible in* λ*:*

$$\mathsf{Adv}^{\mathsf{UF\text{-}CMA}}_{\mathcal{A},\mathsf{IBS}}(\lambda) := \Pr\left[\mathbf{UF\text{-}CMA}^{\mathcal{A}}_{\mathsf{IBS}}(\lambda) \Rightarrow 1\right].$$

Game UF-naCMA$^{\mathcal{A}}_{\mathsf{IBS}}(\lambda)$

$(\mathcal{L}_{id}, \mathcal{L}_m, St) \leftarrow \mathcal{A}(1^\lambda)$
$(\mathsf{mpk}, \mathsf{msk}) \leftarrow \mathsf{Setup}(1^\lambda)$
for $\mathsf{id} \in \mathcal{L}_{id}$:
  $\mathsf{sk_{id}} \leftarrow \mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$
  $\mathcal{L}_{sk} := \mathcal{L}_{sk} \cup \{\mathsf{sk_{id}}\}$
for $(\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$:
  $\sigma \leftarrow \mathsf{Sig}(\mathsf{sk_{id}}, \mathsf{m})$
  $\mathcal{L}_{sig} := \mathcal{L}_{sig} \cup \{\sigma\}$
$(\mathsf{id}^*, \mathsf{m}^*, \sigma^*) \leftarrow \mathcal{A}^{\mathsf{H}}(St, \mathsf{mpk}, \mathcal{L}_{sk}, \mathcal{L}_{sig})$
if $\mathsf{id}^* \in \mathcal{L}_{id}$: **return** 0
if $(\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$: **return** 0
return $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}^*, \mathsf{m}^*, \sigma^*)$

Game UF-CMA$^{\mathcal{A}}_{\mathsf{IBS}}(\lambda)$

$(\mathsf{mpk}, \mathsf{msk}) \leftarrow \mathsf{Setup}(1^\lambda)$
$(\mathsf{id}^*, \mathsf{m}^*, \sigma^*) \leftarrow \mathcal{A}^{\textsc{Key},\textsc{Sig},\mathsf{H}}(1^\lambda, \mathsf{mpk})$
if $\mathsf{id}^* \in \mathcal{L}_{id}$: **return** 0
if $(\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$: **return** 0
return $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}^*, \mathsf{m}^*, \sigma^*)$

Oracle $\textsc{Key}(\mathsf{id})$

$\mathcal{L}_{id} := \mathcal{L}_{id} \cup \{\mathsf{id}\}$
return $\mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$

Oracle $\textsc{Sig}(\mathsf{id}, \mathsf{m})$

$\mathcal{L}_m := \mathcal{L}_m \cup \{(\mathsf{id}, \mathsf{m})\}$
$\mathsf{sk_{id}} \leftarrow \mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$
return $\sigma \leftarrow \mathsf{Sig}(\mathsf{sk_{id}}, \mathsf{m})$

Fig. 1. The games **UF-naCMA** (left) and **UF-CMA** (right) for an identity-based signature scheme IBS and a random oracle H (in the standard model case, the oracle H is removed).

3 Generic Constructions of Adaptively Secure IBS

In this section we will provide two transformations from non-adaptively secure identity-based signature schemes to adaptively secure ones. Let $\mathsf{IBS}' = (\mathsf{Setup}', \mathsf{KeyExt}', \mathsf{Sig}', \mathsf{Ver}')$ be an identity-based signature scheme with identity space $\mathcal{ID}$ and message space $\mathcal{M}$, $\mathsf{CHF} = (\mathsf{CHGen}, \mathsf{CHash}, \mathsf{CHColl})$ a chameleon hash function, $\mathsf{H}_1 : \{0,1\}^* \to \mathcal{ID}, \mathsf{H}_2 : \{0,1\}^* \to \mathcal{M}$ random oracles and $\ell = \ell(\lambda) \in \mathbb{N}$. We define new identity-based signature schemes IBS in Fig. 2 and $\mathsf{IBS_{ROM}}$ in Fig. 5. Note that the first transformation works in the standard model, whereas the second one uses random oracles. The reason why we also introduce this second transformation is that our non-adaptively secure construction from lattices uses random oracles already, so we can use the second transformation which is more efficient and without relying on additional primitives such as chameleon hash functions.

3.1 Transformation in the Standard Model

Here we will show that if IBS' is non-adaptively secure and CHF is a collision-resistant chameleon hash, then IBS, defined in Fig. 2, is adaptively secure. It is clear that if IBS' is ρ-complete, then IBS is ρ-complete as well.

Theorem 1. *Let* IBS' *be an identity-based signature scheme and* CHF *be an* $\varepsilon_{\mathsf{trap}}$*-chameleon hash function. If* IBS' *is* UF-naCMA *secure and* CHF *is collision resistant, then* IBS *is* UF-CMA *secure. In particular, for every algorithm* $\mathcal{A}$ *making at most* Q_S *signing queries and* Q_C *secret key queries there are algorithms* $\mathcal{B}_1$ *and* $\mathcal{B}_2$ *such that*

$$\mathsf{Adv}^{\mathsf{UF\text{-}CMA}}_{\mathcal{A},\mathsf{IBS}}(\lambda) \leq \mathsf{Adv}^{\mathsf{coll}}_{\mathcal{B}_1,\mathsf{CHF}}(\lambda) + \mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{B}_2,\mathsf{IBS}'}(\lambda) + (Q_C + 2Q_S)\varepsilon_{\mathsf{trap}}.$$

Alg $\mathsf{Setup}(1^\lambda)$
$(\mathsf{hk}, \mathsf{td}) \leftarrow \mathsf{CHGen}(1^\lambda)$
$(\mathsf{mpk}', \mathsf{msk}') \leftarrow \mathsf{Setup}'(1^\lambda)$
$\mathsf{mpk} := (\mathsf{mpk}', \mathsf{hk}), \mathsf{msk} := \mathsf{msk}'$
return $(\mathsf{mpk}, \mathsf{msk})$

Alg $\mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$
$r \leftarrow \mathcal{R}_{\mathsf{hk}}$
$\mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$
$\mathsf{sk}'_{\mathsf{id}} \leftarrow \mathsf{KeyExt}'(\mathsf{msk}', \mathsf{id}')$
return $(r, \mathsf{sk}'_{\mathsf{id}})$

Alg $\mathsf{Sig}(\mathsf{sk}_{\mathsf{id}}, \mathsf{m})$
let $\mathsf{sk}_{\mathsf{id}} = (r, \mathsf{sk}'_{\mathsf{id}})$
$s \leftarrow \mathcal{R}_{\mathsf{hk}}$
$\sigma' \leftarrow \mathsf{Sig}'(\mathsf{sk}'_{\mathsf{id}}, \mathsf{CHash}(\mathsf{hk}, \mathsf{m}; s))$
return (r, s, σ')

Alg $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}, \mathsf{m}, \sigma)$
let $\sigma = (r, s, \sigma')$
$\mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$
$\mathsf{m}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}; s)$
return $\mathsf{Ver}'(\mathsf{mpk}', \mathsf{id}', \mathsf{m}', \sigma')$

Fig. 2. Our adaptively secure $\mathsf{IBS} = (\mathsf{Setup}, \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$ for a given non-adaptively secure $\mathsf{IBS}' = (\mathsf{Setup}', \mathsf{KeyExt}', \mathsf{Sig}', \mathsf{Ver}')$ and a chameleon hash function $\mathsf{CHF} = (\mathsf{CHGen}, \mathsf{CHash}, \mathsf{CHColl})$.

and $\mathbf{T}(\mathcal{B}_1) \approx \mathbf{T}(\mathcal{A}), \mathbf{T}(\mathcal{B}_2) \approx \mathbf{T}(\mathcal{A})$.

Proof. We prove the statement via a games $\mathbf{G}_0$ and $\mathbf{G}_1$ and reductions $\mathcal{B}_1$ and $\mathcal{B}_2$. Games $\mathbf{G}_0, \mathbf{G}_1$ are formally presented in Fig. 3. In every game $i \in \{0, 1\}$, we denote the advantage of adversary $\mathcal{A}$ as $\mathsf{Adv}_i(\mathcal{A}) := \Pr\left[\mathbf{G}_i^{\mathcal{A}} \Rightarrow 1\right]$. Game $\mathbf{G}_0$ is the original game **UF-CMA**, hence we aim to bound $\mathsf{Adv}_0(\mathcal{A})$. Game $\mathbf{G}_1$

Game $\mathbf{G}_0$,$\mathbf{G}_1$
$(\mathsf{hk}, \mathsf{td}) \leftarrow \mathsf{CHGen}(1^\lambda)$
$(\mathsf{mpk}', \mathsf{msk}') \leftarrow \mathsf{Setup}'(1^\lambda)$
$\mathsf{mpk} := (\mathsf{mpk}', \mathsf{hk}), \mathsf{msk} := \mathsf{msk}'$
$(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*)) \leftarrow \mathcal{A}^{\textsc{Key},\textsc{Sig}}(\mathsf{mpk})$
if $\mathsf{id}^* \in \mathcal{L}_{id}$: **return** 0
if $(\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$: **return** 0
$\mathsf{id}^*_h := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*)$
$\mathsf{m}^*_h := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}^*; s^*)$
if $\exists(\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id} : \mathsf{id}^*_h = \mathsf{id}'$:
  $\mathsf{bad}_1 = 1$, **return** 0
if $\exists((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s)) \in \mathcal{H}_m$:
$\mathsf{id}^*_h = \mathsf{id}' \wedge \mathsf{m}^*_h = \mathsf{m}'$:
    $\mathsf{bad}_2 = 1$, **return** 0
return $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}^*, \mathsf{m}^*, \sigma^*)$

Oracle $\textsc{Key}(\mathsf{id})$
$\mathcal{L}_{id} := \mathcal{L}_{id} \cup \{\mathsf{id}\}$
$r \leftarrow \mathcal{R}_{\mathsf{hk}}, \mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$
$\mathsf{sk}'_{\mathsf{id}} \leftarrow \mathsf{KeyExt}'(\mathsf{msk}', \mathsf{id}')$
$x := (\mathsf{id}', \mathsf{id}, r)$
$\mathcal{H}_{id} := \mathcal{H}_{id} \cup \{x\}$
return $(r, \mathsf{sk}'_{\mathsf{id}})$

Oracle $\textsc{Sig}(\mathsf{id}, \mathsf{m})$
$\mathcal{L}_m := \mathcal{L}_m \cup \{(\mathsf{id}, \mathsf{m})\}$
$r \leftarrow \mathcal{R}_{\mathsf{hk}}, \mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$
$\mathsf{sk}'_{\mathsf{id}} \leftarrow \mathsf{KeyExt}'(\mathsf{msk}', \mathsf{id}')$
$s \leftarrow \mathcal{R}_{\mathsf{hk}}, \mathsf{m}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}; s)$
$\sigma' \leftarrow \mathsf{Sig}'(\mathsf{sk}'_{\mathsf{id}}, \mathsf{m}')$
$x := ((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s))$
$\mathcal{H}_m := \mathcal{H}_m \cup \{x\}$
return (r, s, σ')

Fig. 3. Games $\mathbf{G}_0$ and $\mathbf{G}_1$ in the proof of Thm. 1. The shaded statements are only executed in $\mathbf{G}_1$.

keeps track of the hashed identities and messages for all key and signing queries. That is, it holds lists $\mathcal{H}_m$ and $\mathcal{H}_{id}$ such that $(\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id}$ means that the

adversary asked for a secret key for identity id and when answering the query, the game hashed id to id' using r, i.e. $\mathsf{id}' = \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$. In a similar way, a tuple $((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s))$ is in $\mathcal{H}_m$ if in some signing query, id was hashed to id and m was hashed to m' using randomness r, s respectively. After obtaining $\mathcal{A}$'s forgery $(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*))$, the game checks additional conditions and returns 0 if one of them holds. These are modeled as the events $\mathsf{bad}_1, \mathsf{bad}_2$. Setting $\mathsf{bad} := \mathsf{bad}_1 \vee \mathsf{bad}_2$ we can bound the difference of both games by

$$|\mathsf{Adv}_0(\mathcal{A}) - \mathsf{Adv}_1(\mathcal{A})| \leq \Pr[\mathsf{bad}].$$

Next, consider the definition of bad_1:

$$\mathsf{bad}_1 := (\exists(\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id} : \mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*) = \mathsf{id}'),$$

which implies that there is a collision

$$\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*) = \mathsf{id}' = \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r).$$

This collision is non-trivial, as $\mathsf{id}^* \notin \mathcal{L}_{id}$ and hence $\mathsf{id}^* \neq \mathsf{id}$. Similarly, a non-trivial collision can be found if bad_2 occurs. Simulating $\mathbf{G}_1$ and checking which collision occurs can be done efficiently without the knowledge of the hash trapdoor td, hence we have a direct reduction $\mathcal{B}_1$ that finds a collision for given hk if bad holds true. Clearly the running time of $\mathcal{B}_1$ is dominated by running $\mathcal{A}$ once. We see that

$$\Pr[\mathsf{bad}] \leq \mathsf{Adv}^{\mathsf{coll}}_{\mathcal{B}_1, \mathsf{CHF}}(\lambda).$$

Finally, we bound the advantage of $\mathcal{A}$ in game $\mathbf{G}_1$ by a reduction $\mathcal{B}_2$ playing the game **UF-naCMA** for the scheme IBS'. The reduction makes use of the trapdoor td and is formally presented in Fig. 4. Reduction $\mathcal{B}_2$ chooses a chameleon hash key and a trapdoor for it and then hashes Q_S many arbitrary values (in our presentation: 0) using randomness r_i, s_i to hash values $\mathsf{id}'_i, \mathsf{m}'_i$. These hash values will then be given to the $\mathsf{UF\text{-}naCMA}$ challenger as the (non-adaptive) signing queries. $\mathcal{B}_2$ will then get a public key mpk' and the signatures σ'_i for these queries. Afterwards, when $\mathcal{A}$ issues the i-th (adaptive) signature query for the pair $(\mathsf{id}, \mathsf{m})$, the reduction uses its trapdoor to find randomness r and s, such that $\mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r) = \mathsf{id}'_i$ and $\mathsf{CHash}(\mathsf{hk}, \mathsf{m}; s) = \mathsf{m}'_i$, i.e.

$$r \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, 0, r_i, \mathsf{id}), s \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, 0, s_i, \mathsf{m}).$$

Then the reduction can simply return (r, s, σ'_i), which is correct, by definition of the scheme. A similar collision strategy is applied to handle the adaptive secret key queries after non-adaptively obtaining secret keys. After obtaining $\mathcal{A}$'s forgery $(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*))$, $\mathcal{B}_2$ checks all the winning conditions and outputs $(\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*), \mathsf{CHash}(\mathsf{hk}, \mathsf{m}^*; s^*), \sigma^*)$. It follows from the properties of the chameleon hash function that this collision finding using the trapdoor and honest signing are statistically close. To be precise, the statistical distance between $\mathbf{G}_1$ and the game simulated by $\mathcal{B}_2$ can be bounded by $(Q_C + 2Q_S)\varepsilon_{\mathsf{trap}}$, as $\mathcal{B}_2$ applies CHColl once per secret key query and twice per signing query.

Alg $\mathcal{B}_2(1^\lambda)$

$(\mathsf{hk}, \mathsf{td}) \leftarrow \mathsf{CHGen}(1^\lambda)$
for $i \in [Q_S]$:
  $s_i \leftarrow \mathcal{R}_{\mathsf{hk}}$
  $\mathsf{m}' := \mathsf{CHash}(\mathsf{hk}, 0; s_i)$
  $r_i \leftarrow \mathcal{R}_{\mathsf{hk}}$
  $\mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, 0; r_i)$
  $\mathcal{L}_m{}' := \mathcal{L}_m{}' \cup \{(\mathsf{id}', \mathsf{m}')\}$
for $i \in [Q_C]$:
  $\bar{r}_i \leftarrow \mathcal{R}_{\mathsf{hk}}$
  $\mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, 0; \bar{r}_i)$
  $\mathcal{L}_{id}{}' := \mathcal{L}_{id}{}' \cup \{\mathsf{id}'\}$
$St := \{\mathsf{hk}, \mathsf{td}, (\bar{r}_i)_i, (s_i, r_i)_i\}$
return $(\mathcal{L}_{id}{}', \mathcal{L}_m{}', St)$

Oracle $\textsc{Key}(\mathsf{id})$

$\mathsf{ctr}_{key} := \mathsf{ctr}_{key} + 1$
$i := \mathsf{ctr}_{key}$
$\mathcal{L}_{id} := \mathcal{L}_{id} \cup \{\mathsf{id}\}$
$r \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, 0, \bar{r}_i, \mathsf{id})$
$x := (\mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r), \mathsf{id}, r)$
$\mathcal{H}_{id} := \mathcal{H}_{id} \cup \{x\}$
return (r, sk'_i)

Alg $\mathcal{B}_2(St, \mathsf{mpk}', \{\mathsf{sk}'_i\}_i, \{\sigma'_i\}_i)$

$\mathsf{mpk} := (\mathsf{mpk}', \mathsf{hk})$
$(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*)) \leftarrow \mathcal{A}^{\textsc{Key},\textsc{Sig}}(\mathsf{mpk})$
if $\mathsf{id}^* \in \mathcal{L}_{id}$: **return** 0
if $(\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$: **return** 0
$\mathsf{id}^*_h := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*)$
$\mathsf{m}^*_h := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}^*; s^*)$
if $\exists(\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id} : \mathsf{id}^*_h = \mathsf{id}'$:
  $\mathsf{bad}_1 = 1$, **return** 0
if $\exists((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s)) \in \mathcal{H}_m$:
$\mathsf{id}^*_h = \mathsf{id}' \wedge \mathsf{m}^*_h = \mathsf{m}'$:
    $\mathsf{bad}_2 = 1$, **return** 0
return $(\mathsf{id}^*_h, \mathsf{m}^*_h, \sigma^*)$

Oracle $\textsc{Sig}(\mathsf{id}, \mathsf{m})$

$\mathsf{ctr}_{sig} := \mathsf{ctr}_{sig} + 1, i := \mathsf{ctr}_{sig}$
$\mathcal{L}_m := \mathcal{L}_m \cup \{(\mathsf{id}, \mathsf{m})\}$
$r \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, 0, r_i, \mathsf{id})$
$s \leftarrow \mathsf{CHColl}(\mathsf{hk}, \mathsf{td}, 0, s_i, \mathsf{m})$
$\mathsf{id}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{id}; r)$
$\mathsf{m}' := \mathsf{CHash}(\mathsf{hk}, \mathsf{m}; s)$
$x := ((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s))$
$\mathcal{H}_m := \mathcal{H}_m \cup \{x\}$
return (r, s, σ'_i)

Fig. 4. Reduction $\mathcal{B}_2$ in the proof of Thm. 1 simulating game $\mathbf{G}_1$ for adversary $\mathcal{A}$ and playing the game **UF-naCMA** for the scheme IBS'.

Let us now argue that $\mathcal{B}_2$ wins the game **UF-naCMA**, assuming $\mathcal{A}$ wins. By definition of the verification algorithm of the scheme, if $\mathcal{A}$ outputs a valid signature (r^*, s^*, σ^*) for message m^* and id^*, then σ^* is a valid signature for identity $\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*)$ and message $\mathsf{CHash}(\mathsf{hk}, \mathsf{m}^*; s^*)$ with respect to IBS'. Hence we only need to check freshness: For the sake of contradiction, assume the secret key of $\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*)$ was (non-adaptively) queried by $\mathcal{B}_2$. Then there is some $i \in [Q_C]$ such that $\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*) = \mathsf{CHash}(\mathsf{hk}, 0; \bar{r}_i)$. The way $\mathcal{B}_2$ answers signature queries tells us that $(\mathsf{CHash}(\mathsf{hk}, 0; \bar{r}_i), \mathsf{id}, r) \in \mathcal{H}_{id}$ for the i-th key query id and some randomness r. This is exactly the definition of event bad_1, which we ruled out before. An analogous argument using bad_2 shows that $(\mathsf{CHash}(\mathsf{hk}, \mathsf{id}^*; r^*), \mathsf{CHash}(\mathsf{hk}, \mathsf{m}^*; s^*))$ was not queried by $\mathcal{B}_2$. Thus, we have

$$\mathsf{Adv}_1(\mathcal{A}) \leq \mathsf{negl}(\lambda) + \mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{B}_2, \mathsf{IBS}'}(\lambda).$$

Finally, the running time of $\mathcal{B}_2$ is dominated by evaluating the polynomial time chameleon hash and running adversary $\mathcal{A}$. $\square$

3.2 Transformation in the Random Oracle Model

Next, we will show that if IBS' is non-adaptively secure and $\ell \in \omega(\log \lambda)$, then $\mathsf{IBS}_{\mathsf{ROM}}$, defined in Fig. 5, is adaptively secure. Clearly, if IBS' is ρ-complete, then $\mathsf{IBS}_{\mathsf{ROM}}$ is also ρ-complete.

Alg $\mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$	**Alg** $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}, \mathsf{m}, \sigma)$
01 $r \xleftarrow{\$} \{0,1\}^\ell, \mathsf{id}' \leftarrow \mathsf{H}_1(\mathsf{id}, r)$	05 **let** $\sigma = (r, s, \sigma')$
02 **return** $(r, \mathsf{KeyExt}'(\mathsf{msk}', \mathsf{id}'))$	06 $\mathsf{id}' \leftarrow \mathsf{H}_1(\mathsf{id}, r)$
	07 $\mathsf{m}' \leftarrow \mathsf{H}_2(\mathsf{m}, s)$
Alg $\mathsf{Sig}(\mathsf{sk}_{\mathsf{id}} = (r, \mathsf{sk}'_{\mathsf{id}}), \mathsf{m})$	08 $v := \mathsf{Ver}'(\mathsf{mpk}', \mathsf{id}', \mathsf{m}', \sigma')$
03 $s \xleftarrow{\$} \{0,1\}^\ell, \mathsf{m}' \leftarrow \mathsf{H}_2(\mathsf{m}, s)$	09 **return** v
04 **return** $(r, s, \mathsf{Sig}'(\mathsf{sk}'_{\mathsf{id}}, \mathsf{m}'))$	

Fig. 5. Our adaptively secure $\mathsf{IBS}_{\mathsf{ROM}} = (\mathsf{Setup} := \mathsf{Setup}', \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$ for a non-adaptively secure $\mathsf{IBS}' = (\mathsf{Setup}', \mathsf{KeyExt}', \mathsf{Sig}', \mathsf{Ver}')$ with random oracles $\mathsf{H}_1, \mathsf{H}_2$ and a natural number $\ell = \ell(\lambda)$.

Theorem 2. *Let* IBS' *be an identity-based signature scheme,* $\mathsf{H}_1 : \{0,1\}^* \to \mathcal{ID}, \mathsf{H}_2 : \{0,1\}^* \to \mathcal{M}$ *be random oracles and* $\ell = \ell(\lambda) \in \omega(\log(\lambda))$*. If* IBS' *is* $\mathsf{UF\text{-}naCMA}$ *secure, then* $\mathsf{IBS}_{\mathsf{ROM}}$ *is* $\mathsf{UF\text{-}CMA}$ *secure. In particular, for every algorithm* $\mathcal{A}$ *making at most* Q_S *signing queries,* Q_C *secret key queries and* Q_H *hash queries (including the indirect ones induced by singing and key queries) there is an algorithm* $\mathcal{B}$ *such that* $\mathbf{T}(\mathcal{B}) \approx \mathbf{T}(\mathcal{A})$ *and*

$$\mathsf{Adv}^{\mathsf{UF\text{-}CMA}}_{\mathcal{A},\mathsf{IBS}_{\mathsf{ROM}}}(\lambda) \leq \mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{B},\mathsf{IBS}'}(\lambda) + (Q_C + 2Q_S)\frac{Q_H}{2^\ell} + \frac{Q_C}{|\mathcal{ID}|} + \frac{Q_S}{|\mathcal{ID}||\mathcal{M}|}.$$

Proof. We will sketch the proof via games $\mathbf{G}_0, \mathbf{G}_1, \mathbf{G}_2$ and denote the corresponding advantage of $\mathcal{A}$ in $\mathbf{G}_i$ by $\mathsf{Adv}_i(\mathcal{A}) := \Pr\left[\mathbf{G}_i^{\mathcal{A}} \Rightarrow 1\right]$. Game $\mathbf{G}_0$ is the original game **UF-CMA**.

Game $\mathbf{G}_1$ holds a variable bad_0 which is set to 1 whenever the hash value $\mathsf{H}_1(\mathsf{id}, r)$ or $\mathsf{H}_2(\mathsf{m}, s)$ in a signing query or a secret key query already has been defined. The game aborts if this variable is set. Thus it is clear that

$$|\mathsf{Adv}_0(\mathcal{A}) - \mathsf{Adv}_1(\mathcal{A})| \leq \Pr[\mathsf{bad}_0].$$

To analyze the probability of this event, we define events $\mathsf{bad}_{key,i}, i \in [Q_C]$ indicating that bad_0 was set to true in the i-th key query. Similarly we define the events $\mathsf{bad}_{sig,id,i}$ and $\mathsf{bad}_{sig,m,i}$ for $i \in [Q_S]$. The probabilities for these events can be bounded by $Q_H/2^\ell$ and we get

$$\begin{aligned}\Pr[\mathsf{bad}_0] &\leq \sum_{i\in[Q_C]} \Pr[\mathsf{bad}_{key,i}] + \sum_{i\in[Q_S]} (\Pr[\mathsf{bad}_{sig,id,i}] + \Pr[\mathsf{bad}_{sig,m,i}]) \\ &\leq (Q_C + 2Q_S)\frac{Q_H}{2^\ell}.\end{aligned}$$

In game $\mathbf{G}_2$ we add additional bad events $\mathsf{bad}_1, \mathsf{bad}_2$ (these are similar to the events in the proof of Thm. 1). If either of them occurs, the game will return 0. The game holds lists $\mathcal{H}_m$ and $\mathcal{H}_{id}$ such that $(\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id}$ means that the adversary asked for a secret key for identity id and when answering the query, the game hashed id to id' using r, i.e. $\mathsf{id}' = \mathsf{H}_1(\mathsf{id}; r)$. In a similar way, a tuple $((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s))$ is in $\mathcal{H}_m$ if in some signing query, id was hashed to id and m was hashed to m' using randomness r, s respectively. After obtaining $\mathcal{A}$'s forgery $(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*))$, the game checks if the events occur:

$$\mathsf{bad}_1 := (\exists (\mathsf{id}', \mathsf{id}, r) \in \mathcal{H}_{id} : \mathsf{H}_1(\mathsf{id}^*, r^*) = \mathsf{id}')$$
$$\mathsf{bad}_2 := (\exists ((\mathsf{id}', \mathsf{id}, r), (\mathsf{m}', \mathsf{m}, s)) \in \mathcal{H}_m : \mathsf{H}_1(\mathsf{id}^*, r^*) = \mathsf{id}' \wedge \mathsf{H}_2(\mathsf{m}^*, s^*) = \mathsf{m}').$$

Similar to the corresponding step in the proof of Thm. 1, it is easy to see that the events imply collisions for H_1 or H_2. As $\mathcal{H}_{id}$ has Q_C entries, the probability of bad_1 can be upper bounded by $Q_C/|\mathcal{ID}|$. Similarly, the probability of bad_2 can be upper bounded by $Q_S(1/|\mathcal{M}| \cdot 1/|\mathcal{ID}|)$ and we obtain

$$|\mathsf{Adv}_1(\mathcal{A}) - \mathsf{Adv}_2(\mathcal{A})| \leq \Pr[\mathsf{bad}_1 \vee \mathsf{bad}_2] \leq \frac{Q_C}{|\mathcal{ID}|} + \frac{Q_S}{|\mathcal{ID}||\mathcal{M}|}.$$

Finally, we bound $\mathsf{Adv}_2(\mathcal{A})$ by a reduction $\mathcal{B}$ playing the game **UF-naCMA** for the scheme IBS'. Reduction $\mathcal{B}$ prepares all the variables needed to simulated $\mathbf{G}_2$ and then samples randomly

$$(\mathsf{id}'_i, \mathsf{m}'_i) \xleftarrow{\$} \mathcal{ID} \times \mathcal{M}, \mathsf{id}''_j \xleftarrow{\$} \mathcal{ID},$$

for all $i \in [Q_S], j \in [Q_C]$. Then it sends these to its challenger and obtains the public key mpk' as well as signatures σ'_i and secret keys sk'_j for these identities and messages. To answer the j-th key query id, $\mathcal{B}$ samples $r \xleftarrow{\$} \{0,1\}^\ell$, checks for the event bad as $\mathbf{G}_2$ does and programs the random oracle H_1 at (id, r) to be id''_j. It then returns sk'_j. This programming can be done without contradicting previous programming as we exactly ruled out that case by definition of bad. A similar programming strategy is applied for signing queries, programming both H_1 and H_2. In the end, after obtaining $\mathcal{A}$'s forgery $(\mathsf{id}^*, \mathsf{m}^*, (r^*, s^*, \sigma^*))$, reduction $\mathcal{B}$ simply applies random oracle to these values and outputs its own forgery

$$(\mathsf{H}_1(\mathsf{id}^*, r^*), \mathsf{H}_2(\mathsf{m}^*, s^*), \sigma^*).$$

Our definition of events $\mathsf{bad}_1, \mathsf{bad}_2$ makes sure that this forgery is fresh. Then it is clear that the running time of $\mathcal{B}$ is dominated by running $\mathcal{A}$ and we have

$$\mathsf{Adv}_2(\mathcal{A}) \leq \mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{B},\mathsf{IBS}'}(\lambda).$$

□

4 Instantiation from SIS

In this section we construct a non-adaptively secure identity-based signature scheme $\mathsf{IBS}_{\mathsf{SIS}}$ based on the SIS assumption. Combined with the transformation presented in the previous section, we obtain an adaptively secure one.

4.1 Background on Lattices

For any m-dimensional lattice (i.e. discrete additive subgroup of $\mathbb{R}^m$) Λ and vector $\mathbf{c} \in \mathbb{R}^m$ we denote the discrete Gaussian distribution with parameter $s > 0$ over the coset $\mathbf{c} + \Lambda$ by $D_{\mathbf{c}+\Lambda,s}$. More precisely, this is the distribution proportional to $\rho_s(\mathbf{x}) := \exp(-\pi\|\mathbf{x}\|^2/s^2)$ restricted to the coset $\mathbf{c} + \Lambda$. Let $\mathbf{A} \in \mathbb{Z}_q^{n\times m}, m > n$ be a matrix. It defines an m-dimensional q-ary lattice and lattice cosets as follows:

$$\Lambda_q^{\perp}(\mathbf{A}) := \{\mathbf{z} \in \mathbb{Z}^m : \mathbf{A}\mathbf{z} = \mathbf{0} \mod q\},\ \Lambda_{\mathbf{u}}^{\perp}(\mathbf{A}) := \{\mathbf{z} \in \mathbb{Z}^m : \mathbf{A}\mathbf{z} = \mathbf{u} \mod q\}.$$

We recall some standard facts about these lattices. For simplicity, throughout the paper we just deal with a prime modululs q. However, the techniques can be generalized to composite q as well [46]. The following lemma is obtained from Lemma 2.9 in [45] by setting $t = \sqrt{m} + \sqrt{n} \in \omega(\sqrt{\log m})$ and hence doubling the constant.

Lemma 1. *There is some univeral constant $C_0 > 0$ such that the following holds: Let $n, m \in \mathbb{N}$ and $\mathbf{X} \in \mathbb{R}^{n\times m}$ be a random subgaussian matrix wth parameter s. Then we have $s_1(\mathbf{X}) \le C_0 \cdot s \cdot (\sqrt{m} + \sqrt{n})$ except with negligible probability.*

The following facts are from [2,47,50,24,25] and can be obtained by using Lemmas 5.1, 5.2 and 5.3 in [24] and Lemma 4.4 in [47].

Lemma 2. *Let $n, m \in \mathbb{N}$, $q \in \mathbb{P}$ at least polynomial in n, $m \ge 2n \log q$. Consider any $\omega(\sqrt{\log m})$ function and $s \ge \omega(\sqrt{\log m})$. Then for all but a negligible (in n) fraction of all $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ the following distribution is statistically close to uniform over $\mathbb{Z}_q^n$: $\{\mathbf{A}\mathbf{e} \mid \mathbf{e} \leftarrow D_{\mathbb{Z}^m,s}\}$. Furthermore, the conditional distribution of $\mathbf{e} \leftarrow D_{\mathbb{Z}^m,s}$ given $\mathbf{u} = \mathbf{A}\mathbf{e} \mod q$ is exactly $D_{\Lambda_{\mathbf{u}}^{\perp}(\mathbf{A}),s}$.*

Lemma 3. *Let $n \in \mathbb{N}$, $q \in \mathbb{P}$ and $m \ge 2n \log q$. Consider any $\omega(\sqrt{\log m})$ function and $s \ge \omega(\sqrt{\log m})$. Then for all but an at most q^{-n} fraction of all $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ and any vector $\mathbf{u} \in \mathbb{Z}_q^n$, we have $\Pr\left[\|\mathbf{x}\| > s\sqrt{m} \mid \mathbf{x} \leftarrow D_{\Lambda_{\mathbf{u}}^{\perp}(\mathbf{A}),s}\right] \le 2^{-m+1}$.*

Lemma 4. *Let $n \in \mathbb{N}$, $q \in \mathbb{P}$ and $m \ge 2n \log q$. Consider any $\omega(\sqrt{\log m})$ function and $s \ge \omega(\sqrt{\log m})$. Then for all but an at most q^{-n} fraction of all $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ and any vector $\mathbf{u} \in \mathbb{Z}_q^n$, we have $H_\infty\left(D_{\Lambda_{\mathbf{u}}^{\perp}(\mathbf{A}),s}\right) \ge m - 1$.*

Throughout this paper, we let $\mathbf{G}$ be the fixed gadget matrix introduced in [46]. Let $n, m, q \in \mathbb{N}, m \ge n\lceil \log q \rceil$ and $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ be a matrix. A trapdoor for $\mathbf{A}$ is a matrix $\mathbf{R} \in \mathbb{Z}^{(m-n\lceil \log q\rceil)\times n\lceil \log q\rceil}$ such that $\mathbf{A}[-\mathbf{R}^t \mid \mathbf{I}_{n\lceil \log q\rceil}]^t = \mathbf{G}$. The next lemma summarizes the results in [46]. In particular, we obtained the precise statements from Section 5 of [46], we use the statistical instantiation of trapdoors and the constant is $C_1 = \sqrt{s_1(\Sigma_{\mathbf{G}}) + 2} \le 3$ (see [46]).

Lemma 5. *Let C_0 be the constant from Lem. 1. There are PPT algorithms* $\mathsf{GenTrap}, \mathsf{SampleD}$ *and* $\mathsf{DelTrap}$ *and constants $C_1 \le 3$ such that for $n, q, m \in \mathbb{N}, q \ge 2, m \ge 3n \log q, w := n\lceil \log q\rceil$ and any $\omega(\sqrt{\log n})$ function the following holds with overwhelming probability over all random choices:*

- *For any* $s \geq \omega(\sqrt{\log n})$ *the algorithm* $\mathsf{GenTrap}(1^n, 1^m, s, q)$ *outputs matrices* $\mathbf{A} \in \mathbb{Z}_q^{n\times m}, \mathbf{R} \in \mathbb{Z}^{(m-w)\times w}$ *such that* $\mathbf{A}$ *is statistically close to uniform,* $\mathbf{R}$ *is a trapdoor for* $\mathbf{A}$ *with entries sampled from* $D_{\mathbb{Z},s}$ *and* $s_1(\mathbf{R}) \leq s \cdot C_0 \cdot (\sqrt{m-w} + \sqrt{w})$.
- *For any matrix* $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ *with trapdoor* $\mathbf{R}$*, for any* $\mathbf{u} \in \mathbb{Z}_q^n$ *and any* $s \geq C_1 \cdot \sqrt{s_1(\mathbf{R})^2 + 1} \cdot \omega(\sqrt{\log n})$*, the following distribution is statistically close to* $D_{\Lambda_{\mathbf{u}}^{\perp}(\mathbf{A}),s}$*:*
$$\{\mathbf{z} | \mathbf{z} \leftarrow \mathsf{SampleD}(\mathbf{A}, \mathbf{R}, \mathbf{u}, s)\}.$$
- *For any matrix* $\mathbf{A} \in \mathbb{Z}_q^{n\times m}$ *with trapdoor* $\mathbf{R}$*, any matrix* $\mathbf{A}' \in \mathbb{Z}_q^{n\times w}$ *and any* $s \geq C_1 \cdot \sqrt{s_1(\mathbf{R})^2 + 1} \cdot \omega(\sqrt{\log n})$*,* $\mathsf{DelTrap}([\mathbf{A} \mid \mathbf{A}'], \mathbf{R}, s)$ *outputs a trapdoor* $\mathbf{R}' \in \mathbb{Z}_q^{m\times w}$ *for* $[\mathbf{A} \mid \mathbf{A}']$ *with distribution independent of* $\mathbf{R}$ *and* $s_1(\mathbf{R}') \leq s \cdot C_0 \cdot (\sqrt{m} + \sqrt{w})$*. Further, for* $\tilde{s} \geq \omega(\sqrt{\log n})$ *and under the same conditions, the following distributions are statistically close:*
$$\left\{(\mathbf{A}, \mathbf{A}', \mathbf{R}') \middle| \begin{array}{c}(\mathbf{A}, \mathbf{R}) \leftarrow \mathsf{GenTrap}(1^n, 1^m, \tilde{s}, q), \mathbf{A}' \xleftarrow{\$} \mathbb{Z}_q^{n\times w}, \\ \mathbf{R}' \leftarrow \mathsf{DelTrap}([\mathbf{A} \mid \mathbf{A}'], \mathbf{R}, s)\end{array}\right\}$$
and
$$\left\{(\mathbf{A}, \mathbf{A}', \mathbf{R}') \middle| (\mathbf{A}, \mathbf{R}) \leftarrow \mathsf{GenTrap}(1^n, 1^m, \tilde{s}, q), \mathbf{R}' \leftarrow D_{\mathbb{Z},s}^{m\times w}, \mathbf{A}' := \mathbf{A}\mathbf{R}' + \mathbf{G}\right\}.$$

Definition 5 (Short Integer Solution Assumption (SIS)). *Let* $\lambda \in \mathbb{N}, n = n(\lambda), m = m(\lambda), \beta = \beta(\lambda) \in \mathbb{N}$ *and* $q = q(n)$ *be prime number. We say that the* $\mathsf{SIS}_{n,m,q,\beta}$ *assumption holds, if for every* PPT *algorithm* $\mathcal{A}$ *the following advantage is negligible in* λ*:*
$$\mathsf{Adv}_{\mathcal{A}}^{\mathsf{SIS}_{n,m,q,\beta}}(\lambda) := \Pr\left[\mathbf{A}\mathbf{z} = \mathbf{0} \wedge \mathbf{z} \neq \mathbf{0} \wedge \|\mathbf{z}\| \leq \beta \mid \mathbf{A} \xleftarrow{\$} \mathbb{Z}_q^{n\times m}, \mathbf{z} \leftarrow \mathcal{A}(\mathbf{A})\right].$$

The hardness of SIS for certain parameters is supported by several worst-case to average-case reductions, see [2,47,25].

4.2 Construction

Now we are ready to present our construction. The scheme is presented in Fig. 6. Its main parameters are SIS parameters $n \in \mathbb{N}, q \in \mathbb{P}, m \geq 3n \log q, \beta > 0$. We also need Gaussian parameters $s_0, s, s', s'', \tilde{s} \geq \omega(\sqrt{\log m})$ (needed for regularity, Lem. 2), where the parameter $\tilde{s}$ is only used in the proof, s_0, s, s', s'' satisfy the conditions for Lem. 5 and β is large enough:

$$\begin{aligned}
s &\geq C_1 \sqrt{s_0^2 C_0^2 (\sqrt{m - n\lceil \log q \rceil} + \sqrt{n\lceil \log q \rceil})^2 + 1} \cdot \omega(\sqrt{\log n}) \\
s' &\geq C_1 \sqrt{s^2 C_0^2 (\sqrt{m} + \sqrt{n\lceil \log q \rceil})^2 + 1} \cdot \omega(\sqrt{\log n}) \\
s'' &\geq C_1 \sqrt{s'^2 C_0^2 (\sqrt{m + n\lceil \log q \rceil} + \sqrt{n\lceil \log q \rceil})^2 + 1} \cdot \omega(\sqrt{\log n}) \\
\beta &\geq (1 + 2C_0 \tilde{s}(\sqrt{m} + \sqrt{n\lceil \log q \rceil}))s'' \sqrt{m + 2n\lceil \log q \rceil}.
\end{aligned}$$

Alg $\mathsf{Setup}(1^\lambda)$	**Alg** $\mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$
set parameters as in the text.	$\mathbf{H}_1 \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
$(\mathbf{A}, \mathbf{T}_\mathbf{A}) \leftarrow \mathsf{GenTrap}(1^n, 1^m, s_0, q)$	$\mathbf{F}_\mathsf{id} := [\mathbf{A} \mid \mathbf{H}_1]$
$\mathsf{mpk} := \mathbf{A} \in \mathbb{Z}_q^{n \times m}, \mathsf{msk} := \mathbf{T}_\mathbf{A}$	$\mathbf{T}_\mathsf{id} \leftarrow \mathsf{DelTrap}(\mathbf{F}_\mathsf{id}, \mathbf{T}_\mathbf{A}, s)$
return $(\mathsf{mpk}, \mathsf{msk})$	**return** $\mathsf{sk}_\mathsf{id} := \mathbf{T}_\mathsf{id}$
Alg $\mathsf{Sig}(\mathsf{sk}_\mathsf{id}, \mathsf{m})$	**Alg** $\mathsf{Ver}(\mathsf{mpk}, \mathsf{id}, \mathsf{m}, \mathbf{z})$
$\mathbf{H}_1 \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$	$\mathbf{H}_1 \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
$\mathbf{H}_2 \leftarrow \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$	$\mathbf{H}_2 \leftarrow \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$
$\mathbf{F}_{\mathsf{id},\mathsf{m}} := [\mathbf{A} \mid \mathbf{H}_1 \mid \mathbf{H}_2]$	$\mathbf{F}_{\mathsf{id},\mathsf{m}} := [\mathbf{A} \mid \mathbf{H}_1 \mid \mathbf{H}_2]$
$\mathbf{T}_{\mathsf{id},\mathsf{m}} \leftarrow \mathsf{DelTrap}(\mathbf{F}_{\mathsf{id},\mathsf{m}}, \mathbf{T}_\mathsf{id}, s')$	**if** $\mathbf{z} = \mathbf{0} \vee \mathbf{F}_{\mathsf{id},\mathsf{m}}\mathbf{z} \neq \mathbf{0}$: **return** 0
$\mathbf{z} \leftarrow \mathsf{SampleD}(\mathbf{F}_{\mathsf{id},\mathsf{m}}, \mathbf{T}_{\mathsf{id},\mathsf{m}}, \mathbf{0}, s'')$	**return** $\|\mathbf{z}\| \leq s''\sqrt{m + 2n\lceil \log q \rceil}$
return $\sigma := \mathbf{z}$	

Fig. 6. The identity-based signature scheme $\mathsf{IBS}_\mathsf{SIS} = (\mathsf{Setup}, \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$, where $\mathsf{H}_1 : \{0,1\}^* \to \mathbb{Z}_q^{n \times n\lceil \log q \rceil}, \mathsf{H}_2 : \{0,1\}^* \to \mathbb{Z}_q^{n \times n\lceil \log q \rceil}$ are random oracles.

Lemma 6. *The identity-based signature scheme* $\mathsf{IBS}_\mathsf{SIS}$ *is* ρ*-complete, where* $\rho \geq 1 - \mathsf{negl}(\lambda)$.

Proof. Consider keys $(\mathsf{mpk} = \mathbf{A}, \mathsf{msk} = \mathbf{T}_\mathbf{A}) \in \mathsf{Setup}(1^\lambda)$, an arbitrary identity id and message m. Let $\mathsf{sk}_\mathsf{id} \in \mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$ and $\mathbf{z} \in \mathsf{Sig}(\mathsf{sk}_\mathsf{id}, \mathsf{m})$. By definition of KeyExt we have that $\mathsf{sk}_\mathsf{id} = \mathbf{T}_\mathsf{id}$ is a trapdoor for the matrix $\mathbf{F}_\mathsf{id} = [\mathbf{A} \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})]$, which is a prefix of $\mathbf{F}_{\mathsf{id},\mathsf{m}} = [\mathbf{A} \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id}) \mid \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})]$. Hence $\mathbf{T}_{\mathsf{id},\mathsf{m}}$ as used in the signature scheme is a trapdoor for $\mathbf{F}_{\mathsf{id},\mathsf{m}}$, by Lem. 5 and the conditions of parameters. The same Lemma tells us that $\mathbf{z}$ is distributed statistically close to $D_{\Lambda_q^\perp(\mathbf{F}_{\mathsf{id},\mathsf{m}}), s''}$, which implies $\mathbf{F}_{\mathsf{id},\mathsf{m}}\mathbf{z} = \mathbf{0}$ and with overwhelming probability (by Lem. 3) $\|\mathbf{z}\| \leq s'' \cdot \sqrt{m + 2n\lceil \log q \rceil}$, which makes Ver accept. □

Theorem 3. *The scheme* $\mathsf{IBS}_\mathsf{SIS}$ *is an* $\mathsf{UF\text{-}naCMA}$ *secure identity-based signature scheme, under the* $\mathsf{SIS}_{n,m,q,\beta}$ *assumption. In particular, for every* PPT *algorithm* $\mathcal{A}$ *there is a* PPT *algorithm* $\mathcal{B}$ *such that*

$$\mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{A},\mathsf{IBS}_\mathsf{SIS}}(\lambda) \leq \mathsf{Adv}^{\mathsf{SIS}_{n,m,q,\beta}}_{\mathcal{B}}(\lambda) + \mathsf{negl}(\lambda)$$

and $\mathbf{T}(\mathcal{B}) \approx \mathbf{T}(\mathcal{A})$.

Proof. The proof is via a reduction $\mathcal{B}$, formally given in Fig. 7. The idea is as follows: The given SIS matrix $\mathbf{A}$ is set as the master public key $\mathsf{mpk} := \mathbf{A}$. For any identity $\mathsf{id} \in \mathcal{L}_{id}$, for which the adversary queries the secret key, $\mathcal{B}$ programs the random oracle $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id}) := \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} + \mathbf{G}$, where $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} \leftarrow D_{\mathbb{Z},s}^{m \times n\lceil \log q \rceil}$ is short. Hence, $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}$ is a trapdoor for $\mathbf{F}_\mathsf{id} := [\mathbf{A} \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})]$ and $\mathcal{B}$ can return it as sk_id. Note that by definition of the non-adaptive security game, $\mathcal{A}$ did not query the random oracle before, hence programming is possible. For all other identities, the hash value will be programmed to $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id}) := \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}$. A similar programming policy is applied for H_2: For every pair $(\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$, for which the adversary wants to know a signature, the random oracle is programmed

Alg $\mathcal{B}(\mathbf{A} \in \mathbb{Z}_q^{n\times m})$

$(\mathcal{L}_{id}, \mathcal{L}_m, St) \leftarrow \mathcal{A}(1^\lambda)$
$\mathsf{mpk} := \mathbf{A}$
for $\mathsf{id} \in \mathcal{L}_{id}$:
  $\hat{\mathbf{R}}_{\mathsf{mpk,id}} \leftarrow D_{\mathbb{Z},s}^{m\times n\lceil \log q\rceil}$
  $h[1, \mathsf{mpk}, \mathsf{id}] := \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk,id}} + \mathbf{G}$
  $\mathsf{sk}_{\mathsf{id}} := \hat{\mathbf{R}}_{\mathsf{mpk,id}}$
  $\mathcal{L}_{sk} := \mathcal{L}_{sk} \cup \{\mathsf{sk}_{\mathsf{id}}\}$

for $(\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$:
  $\mathbf{R}_{\mathsf{mpk,id,m}} \leftarrow D_{\mathbb{Z},s}^{m\times n\lceil \log q\rceil}$
  $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] := \mathbf{A}\mathbf{R}_{\mathsf{mpk,id,m}} + \mathbf{G}$
  $\mathbf{B} := \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
  $\mathbf{C} := h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}]$
  $\mathbf{F}'_{\mathsf{id,m}} := [\mathbf{A} \mid \mathbf{C} \mid \mathbf{B}]$
  $\mathbf{F}_{\mathsf{id,m}} := [\mathbf{A} \mid \mathbf{B} \mid \mathbf{C}]$
  $\mathbf{T}'_{\mathsf{id,m}} \leftarrow \mathsf{DelTrap}(\mathbf{F}'_{\mathsf{id,m}}, \mathbf{R}_{\mathsf{mpk,id,m}}, s')$
  $\mathbf{z} \leftarrow \mathsf{SampleD}(\mathbf{F}'_{\mathsf{id,m}}, \mathbf{T}'_{\mathsf{id,m}}, \mathbf{0}, s'')$
  $\mathbf{z}_{\mathsf{id,m}} := [\mathbf{z}_1^t \mid \mathbf{z}_3^t \mid \mathbf{z}_2^t]^t$
  $\mathcal{L}_{sig} := \mathcal{L}_{sig} \cup \{\mathbf{z}_{\mathsf{id,m}}\}$

$(\mathsf{id}^*, \mathsf{m}^*, \mathbf{z}^*) \leftarrow \mathcal{A}^{\mathsf{H}_1,\mathsf{H}_2}(St, \mathsf{mpk}, \mathcal{L}_{sk}, \mathcal{L}_{sig})$
if $\mathsf{id}^* \in \mathcal{L}_{id} \vee (\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$:
  return $\perp$
if $\mathbf{z}^* > s''\sqrt{m} \vee \mathbf{z}^* = \mathbf{0}$:
  return $\perp$
$\mathbf{B} := \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk,id}^*}, \mathbf{C} := \mathbf{A}\mathbf{R}_{\mathsf{mpk,id}^*,\mathsf{m}^*}$
$\mathbf{F}_{\mathsf{id}^*,\mathsf{m}^*} := [\mathbf{A} \mid \mathbf{B} \mid \mathbf{C}]$
if $\mathbf{F}_{\mathsf{id}^*,\mathsf{m}^*}\mathbf{z}^* \neq \mathbf{0}$: **return** $\perp$
$\mathbf{z} := [\mathbf{I}_m \mid \hat{\mathbf{R}}_{\mathsf{mpk,id}^*} \mid \mathbf{R}_{\mathsf{mpk,id}^*,\mathsf{m}^*}]\mathbf{z}^*$
return $\mathbf{z}$

Oracle $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
if $h[1, \mathsf{mpk}, \mathsf{id}] = \perp$:
  $\hat{\mathbf{R}}_{\mathsf{mpk,id}} \leftarrow D_{\mathbb{Z},\tilde{s}}^{m\times n\lceil \log q\rceil}$
  $h[1, \mathsf{mpk}, \mathsf{id}] := \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk,id}}$
return $h[1, \mathsf{mpk}, \mathsf{id}]$

Oracle $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$
if $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] = \perp$:
  $\mathbf{R}_{\mathsf{mpk,id,m}} \leftarrow D_{\mathbb{Z},\tilde{s}}^{m\times n\lceil \log q\rceil}$
  $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] := \mathbf{A}\mathbf{R}_{\mathsf{mpk,id,m}}$
return $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}]$

Fig. 7. Reduction $\mathcal{B}$, solving the SIS problem using an adversary $\mathcal{A}$ against the UF-naCMA security of $\mathsf{IBS}_{\mathsf{SIS}}$.

as $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m}) := \mathbf{A}\mathbf{R}_{\mathsf{mpk,id,m}} + \mathbf{G}$ for $\mathbf{R}_{\mathsf{mpk,id,m}} \leftarrow D_{\mathbb{Z},s}^{m\times n\lceil \log q\rceil}$. Using $\mathbf{R}_{\mathsf{mpk,id,m}}$ as a trapdoor for $[\mathbf{A} \mid \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})]$ the reduction can compute a trapdoor for $\mathbf{F}'_{\mathsf{id,m}} := [\mathbf{A} \mid \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m}) \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})]$, sample from $D_{\Lambda_q^\perp(\mathbf{F}'_{\mathsf{id,m}}),s''}$ and permute the resulting vector to get a signature as in the real scheme. Again, the random oracle value is not yet defined and can be programmed and other queries are programmed as $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m}) := \mathbf{A}\mathbf{R}_{\mathsf{mpk,id,m}}$. In the end $\mathcal{A}$ will return a forgery $(\mathsf{id}^*, \mathsf{m}^*, \mathbf{z}^*)$. We assume that $\mathcal{A}$ queried all related random oracle queries $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id}^*)$ and $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}^*, \mathsf{m}^*)$ (otherwise we can build a new adversary making the queries after running $\mathcal{A}$ and having the same success probability). If $\mathcal{A}$ is successful, then $\mathsf{id}^* \notin \mathcal{L}_{id}$ and $(\mathsf{id}^*, \mathsf{m}^*) \notin \mathcal{L}_m$, which implies that

$$\mathbf{0} = \mathbf{F}_{\mathsf{id}^*,\mathsf{m}^*}\mathbf{z}^* = [\mathbf{A} \mid \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk,id}^*} \mid \mathbf{A}\mathbf{R}_{\mathsf{mpk,id}^*,\mathsf{m}^*}]\mathbf{z}^*,$$

and hence $\mathcal{B}$ can return

$$\mathbf{z} := [\mathbf{I}_m \mid \hat{\mathbf{R}}_{\mathsf{mpk,id}^*} \mid \mathbf{R}_{\mathsf{mpk,id}^*,\mathsf{m}^*}]\mathbf{z}^*.$$

Note that the running time of the reduction is dominated by running $\mathcal{A}$. Let us now look at the details and show that the simulation is perfect (up to negligible statistical distance) and that $\mathbf{z}$ has the correct length and is not zero. As $s, \tilde{s} > \omega(\sqrt{\log m})$ and $m \geq 2n \log q$, Lem. 2 shows that $\mathbf{A}\mathbf{R}$ is statistically close to uniform for $\mathbf{A} \xleftarrow{\$} \mathbb{Z}_q^{n\times m}$ and $\mathbf{R} \leftarrow D_{\mathbb{Z},\kappa}^{m\times n\lceil \log q\rceil}$ for $\kappa \in \{s, \tilde{s}\}$, hence

the simulation of H_1 and H_2 is statistically close to the real game. Next, the distribution of the secret keys $\mathsf{sk}_{\mathsf{id}} = \hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}$ is statistically close to the real game, which can be obtained by applying the properties of $\mathsf{DelTrap}$ from Lem. 5. Further, $\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}$ is a trapdoor for $[\mathbf{A} \mid \mathbf{A}\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} + \mathbf{G}]$, which is a prefix of $\mathbf{F}'_{\mathsf{id},\mathsf{m}}$ (as defined in Fig. 7) and thus the signature output by $\mathcal{B}$ is statistically close to $D_{\Lambda_q^\perp(\mathbf{F}_{\mathsf{id},\mathsf{m}}),s''}$, as honest signatures are. It remains to show that $\mathbf{z}$ is a suitable solution for SIS: To see that $\mathbf{z}$ is not zero, write $\mathbf{z}^* = [\mathbf{z}_1^* \mid \mathbf{z}_2^*]^t$ where $\mathbf{z}_1^* \in \mathbb{Z}_q^m, \mathbf{z}_2^* \in \mathbb{Z}_q^{2n\lceil \log q\rceil}$ and note that

$$\mathbf{z} = \mathbf{z}_1^* + [\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}_2^*.$$

Now, if $\mathbf{z}_2^* = \mathbf{0}$, then $\mathbf{z} \neq \mathbf{0}$ as $\mathbf{z}_1^* \neq \mathbf{0}$. Otherwise there is some non-zero component $z_{2,j}^* \neq 0, j \in [2n\lceil \log q\rceil]$. Denote the columns of $[\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]$ by $\mathbf{r}_i \in \mathbb{Z}_q^m, i \in [2n\lceil \log q\rceil]$. Then $\mathbf{z} = \mathbf{0}$ implies that

$$-\frac{1}{z_{2,j}^*}(\mathbf{z}_1^* + \sum_{i\neq j} z_{2,i}^*\mathbf{r}_i) = \mathbf{r}_j.$$

Further, note that the only information about $\mathbf{r}_j$ that $\mathcal{A}$ gets is a column of the hash value $\mathsf{H}_1(\mathsf{mpk},\mathsf{id}^*) = \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*}$ (if $j \leq n\lceil \log q\rceil$) or $\mathsf{H}_2(\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*) = \mathbf{A}\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}$ (otherwise). Let $\mathbf{u}$ denote that column. Then from $\mathcal{A}$'s view, $\mathbf{r}_j$ is distributed as $D_{\Lambda_{\mathbf{u}}^\perp(\mathbf{A}),\tilde{s}}$. This distribution has a large min-entropy (with overwhelming probability over $\mathbf{A} \xleftarrow{\$} \mathbb{Z}_q^{n\times m}$) by Lem. 4, and hence the probability that $\mathbf{z} = \mathbf{0}$ is negligible. Finally, by Lem. 1 we have that $s_1(\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*}), s_1(\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}) \leq C_0 \cdot \tilde{s} \cdot (\sqrt{m} + \sqrt{n\lceil \log q\rceil})$ with overwhelming probability. Hence

$$\begin{aligned}\|\mathbf{z}\| &\leq \|\mathbf{z}_1^*\| + \|[\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}_2^*\| \\ &\leq (1 + 2C_0\tilde{s}(\sqrt{m} + \sqrt{n\lceil \log q\rceil}))s''\sqrt{m + 2n\lceil \log q\rceil} \leq \beta,\end{aligned}$$

which finishes the proof. □

Let us note the key and signature sizes (in bits) of our (non-adaptive) scheme :

$$\begin{aligned}|\mathsf{mpk}| &= n \cdot m \cdot \lceil \log(q)\rceil, & |\mathsf{msk}| &= (m - n\lceil \log(q)\rceil) \cdot n \cdot \lceil \log(q)\rceil^2, \\ |\mathsf{sk}_{\mathsf{id}}| &= m \cdot n \cdot \lceil \log(q)\rceil^2, & |\sigma| &= (m + 2 \cdot n \cdot \lceil \log(q)\rceil) \cdot \lceil \log(q)\rceil.\end{aligned}$$

In order to get concrete parameters, we can use an estimation that in every delegation, it is enough (up to constants) that the Gaussian width multiplies with $\sqrt{m} \cdot \omega(\sqrt{\log m})$. For the worst-case to average-case reductions [47,25] to work, we need to choose $q \geq \beta \cdot \mathsf{poly}(n)$, where $\mathsf{poly}(n)$ can grow roughly as $\sqrt{n}$. One obtains that the following example instantiation satisfies all our conditions for large enough n and $n^4 \leq q \leq n^5$ prime:

$$\begin{aligned}m &:= 3n \log q, & s_0 &:= \tilde{s} := \omega(\sqrt{\log m}), \\ s &:= \hat{C} \cdot m^{1/2} \cdot \omega(\sqrt{\log m})^2, & s' &:= \hat{C}^2 \cdot m \cdot \omega(\sqrt{\log m})^3, \\ s'' &:= \hat{C}^3 \cdot m^{3/2} \cdot \omega(\sqrt{\log m})^4, & \beta &:= \tilde{C} \cdot n^{5/2} \cdot \log(n)^{5/2} \cdot \omega(\sqrt{\log m})^5,\end{aligned}$$

where $\hat{C} := 4C_0C_1$ and $\tilde{C} := 48 \cdot 3^{3/2} \cdot 5^{5/2} \cdot \hat{C}^3C_0$ are constants chosen such that the estimation is correct.

5 Instantiation from Ring-SIS

In this section we translate our non-adaptively secure identity-based signature scheme $\mathsf{IBS}_{\mathsf{SIS}}$ based on the SIS assumption to the ring setting. We obtain a non-adaptively secure identity-based signature scheme $\mathsf{IBS}_{\mathsf{RSIS}}$ based on the RSIS assumption. Combined with the transformation presented in Section 3 we obtain an adaptively secure scheme.

5.1 Background on Lattices in the Ring Setting

Before we can introduce our scheme, we need to introduce the ring setting and lemmas analogous to Lem. 1 to 5 for it. For our presentation, we follow the setting in [19,20]. Especially, we use a modulus which is a power of 3.

For the rest of this section, we assume that $n = 2^k \in \Theta(\lambda)$ for $k \in \mathbb{N}$ and define the ring $R = \mathbb{Z}[X]/(X^n + 1)$, which is the ring of integers in the $2n$-th cyclotomic number field. Further, we assume $q = 3^h, h \in \mathbb{N}$ is a power of 3 polynomial in n and define $R_q = R/qR$. There is a natural isomorphism of vector spaces $\mathfrak{cf} : R \to \mathbb{Z}^n$, called the coefficient embedding, with

$$\mathfrak{cf}(\sum_{i=0}^{n-1} \alpha_i X^i) = \begin{pmatrix} \alpha_0 \\ \vdots \\ \alpha_{n-1} \end{pmatrix}.$$

Further, there is an injective ring homomorphism $\mathfrak{rot} : R \to \mathbb{Z}^{n\times n}$ that maps $a \in R$ to the matrix representing the linear transformation $r \mapsto ar$. That is, we define

$$\mathfrak{rot}(a) = [\mathfrak{cf}(a) \mid \cdots \mid \mathfrak{cf}(aX^{n-1})].$$

Both $\mathfrak{cf}$ and $\mathfrak{rot}$ can easily be extended to vectors and matrices over R and to R_q. The following properties follow easily for all $\ell_1, \ell_2 \in \mathbb{N}, s \in R, \mathbf{a}, \mathbf{b} \in R^{\ell_2}, \mathbf{R} \in R^{\ell_1\times\ell_2}$:

$$\mathfrak{cf}(s\mathbf{a}) = \mathfrak{rot}(\mathbf{a})\mathfrak{cf}(s), \qquad \mathfrak{cf}(\mathbf{a}^t\mathbf{b}) = \mathfrak{rot}(\mathbf{a}^t)\mathfrak{cf}(\mathbf{b}),$$
$$\mathfrak{cf}(\mathbf{R}\mathbf{a}) = \mathfrak{rot}(\mathbf{R})\mathfrak{cf}(\mathbf{a}), \qquad \mathfrak{rot}(\mathbf{R}\mathbf{a}) = \mathfrak{rot}(\mathbf{R})\mathfrak{rot}(\mathbf{a}).$$

Further, we use $\mathfrak{cf}$ and $\mathfrak{rot}$ to define norms of vectors and matrices over R:

$$\|r\| := \|\mathfrak{cf}(r)\| \text{ for } r \in R,$$
$$s_1(\mathbf{R}) := s_1(\mathfrak{rot}(\mathbf{R})) \text{ for } \mathbf{R} \in R^{\ell_1\times\ell_2}.$$

We also introduce a distribution of ring elements, vectors and matrices analogous to the discrete Gaussian distribution over $\mathbb{Z}$:

$$D_{R,s} := \mathfrak{cf}^{-1}(D_{\mathbb{Z}^n,s}).$$

Finally, for $\mathbf{a} \in R^\ell, u \in R$ we define q-ary lattices over R similar to the q-ary lattices over $\mathbb{Z}$:

$$\Lambda_q^\perp(\mathbf{a}^t) := \{\mathbf{z} \in R^\ell : \mathbf{a}^t\mathbf{z} = 0 \mod q\},\ \Lambda_u^\perp(\mathbf{a}^t) := \{\mathbf{z} \in R^\ell : \mathbf{a}^t\mathbf{z} = u \mod q\}.$$

Next, we introduce lemmas analogous to Lem. 1 to 5. The first lemma is stated as Fact 6 in [20]. For all lemmas, we assume that n, R, q are as above.

Lemma 7. *There is some constant $C_{0,r}$ such that the following holds: Let $\ell_1, \ell_2 \in \mathbb{N}, s > 0$ and $\mathbf{R} \leftarrow D_{R,s}^{\ell_1 \times \ell_2}$. Then we have $s_1(\mathbf{R}) \leq C_{0,r} \cdot s\sqrt{n} \cdot (\sqrt{\ell_1} + \sqrt{\ell_2} + \omega(\sqrt{\log n}))$ except with negligible probability.*

The first part of the next lemma is literally stated in [20], Lemma 7. For the second part, one can follow the proof in [24], Lemma 5.2 using $\mathfrak{rot}(\mathbf{a}^t)$.

Lemma 8. *Let $\ell \in \mathbb{N}, \ell \geq 2\lceil \log q \rceil + 2$. Consider any $\omega(\sqrt{\log \ell n})$ function and $s \geq \omega(\sqrt{\log \ell n})$. Then for all but a negligible (in n) fraction of all $\mathbf{a} \in R_q^\ell$ the following distribution is statistically close to uniform over R_q: $\{\mathbf{a}^t\mathbf{e} \mid \mathbf{e} \leftarrow D_{R,s}^\ell\}$. Furthermore, the conditional distribution of $\mathbf{e} \leftarrow D_{R,s}^\ell$ given $u = \mathbf{a}^t\mathbf{e} \mod q$ is exactly $D_{\Lambda_u^\perp(\mathbf{a}^t),s}$.*

The next lemma follows easily by applying $\mathfrak{cf}$ to standard Gaussian tail bounds over $\mathbb{Z}$, see e.g. [47,24].

Lemma 9. *Consider $\ell \in \mathbb{N}$ and any $\omega(\sqrt{\log \ell n})$ function and $s \geq \omega(\sqrt{\log \ell n})$. Then we have*

$$\Pr\left[\|\mathbf{x}\| > s\sqrt{\ell n} \mid \mathbf{x} \leftarrow D_{R,s}^\ell\right] \leq \mathsf{negl}(\lambda).$$

We can combine the previous two lemmas to obtain the following lemma.

Lemma 10. *Let $\ell \in \mathbb{N}, \ell \geq 2\lceil \log q \rceil + 2$. Consider any $\omega(\sqrt{\log \ell n})$ function and $s \geq \omega(\sqrt{\log \ell n})$. Then for all but a negligible (in n) fraction of all $\mathbf{a} \in R_q^\ell$ and any $u \in R_q$, we have*

$$\Pr\left[\|\mathbf{x}\| > s\sqrt{\ell n} \mid \mathbf{x} \leftarrow D_{\Lambda_u^\perp(\mathbf{a}^t),s}\right] \leq \mathsf{negl}(\lambda).$$

The next lemma is stated in [20], Corollary 8.

Lemma 11. *Let $\ell \in \mathbb{N}, \ell \geq 2\lceil \log q \rceil + 3$. Consider any $\omega(\sqrt{\log \ell n})$ function and $s \geq \omega(\sqrt{\log \ell n})$. Then with overwhelming probability over the choice $\mathbf{a}^t \xleftarrow{\$} R_q^{1\times\ell}$ the following holds: For any $u \in R_q$ and any $\mathbf{v} \in R^\ell \setminus \{\mathbf{0}\}$ we have $H_\infty\left(\mathbf{v}^t D_{\Lambda_u^\perp(\mathbf{a}^t),s}\right) \geq \Omega(n)$.*

Next, we introduce trapdoors [46] for lattices in the ring setting. Contrary to our presentation of trapdoors in the plain setting, we use base 3, as in [19,20]. First, we define a ring analogue of the gadget matrix $\mathbf{G}$:

$$\mathbf{g}^t := (1, 3, 9, \ldots, 3^{h-1}) \in R^{1\times h},$$

where $q = 3^h$. If $\mathbf{G}$ is the standard gadget matrix with base 3, then it is easy to see that

$$\mathfrak{rot}(\mathbf{g}^t) = \mathbf{G}\mathbf{P}$$

for some permutation matrix $\mathbf{P} \in \{0,1\}^{hn\times hn}$. For $\ell \geq hn$, we say that a matrix $\mathbf{R} \in R^{(\ell-h)\times h}$ is a trapdoor for $\mathbf{a}^t \in R^{1\times\ell}$ if $\mathbf{a}^t[-\mathbf{R}^t \mid \mathbf{I}_{nh}] = \mathbf{g}^t$. Note that this

also implies that in the plain setting $\mathfrak{rot}(\mathbf{R}) \in \mathbb{Z}_q^{(\ell n - hn)\times hn}$ is a trapdoor for $\mathfrak{rot}(\mathbf{a}^t) \in \mathbb{Z}_q^{\times hn}$ with respect to gadget matrix $\mathbf{GP}$. The trapdoor algorithms in [46] are not sensitive to column permutations. Hence, we can use them to obtain the following lemma, summarizing trapdoors in the ring setting, where the claims about $\mathsf{GenTrapR}$ and $\mathsf{DelTrapR}$ follow by using Lem. 8. The statements can also be found in [20], Section 2.4.

Lemma 12. *Let $C_{0,r}$ be the constant from Lem. 7. There are PPT algorithms $\mathsf{GenTrapR}, \mathsf{SampleDR}$ and $\mathsf{DelTrapR}$ and constants $C_{1,r} \leq 3$ such that for $\ell \geq 2\lceil \log q \rceil + 2$ and any $\omega(\sqrt{\log \ell n})$ function the following holds with overwhelming probability over all random choices:*

- *For any $s \geq \omega(\sqrt{\log \ell n})$ the algorithm $\mathsf{GenTrapR}(1^n, 1^\ell, s, q)$ outputs $\mathbf{a}^t \in R_q^{1\times \ell}, \mathbf{R} \in R^{(\ell-h)\times h}$ such that $\mathbf{a}^t$ is statistically close to uniform, $\mathbf{R}$ is a trapdoor for $\mathbf{a}^t$ with entries sampled from $D_{R,s}$ and $s_1(\mathbf{R}) \leq C_{0,r} \cdot s\sqrt{n} \cdot (\sqrt{\ell - h} + \sqrt{h} + \omega(\sqrt{\log n}))$.*
- *For any $\mathbf{a} \in R_q^{1\times \ell}$ with trapdoor $\mathbf{R}$, for any $u \in R_q$ and any $s \geq C_{1,r} \cdot \sqrt{s_1(\mathbf{R})^2 + 1} \cdot \omega(\sqrt{\log \ell n})$, the following distribution is statistically close to $D_{\Lambda_u^\perp(\mathbf{a}^t),s}$:*
$$\left\{\mathbf{z} \middle| \mathbf{z} \leftarrow \mathsf{SampleDR}(\mathbf{a}^t, \mathbf{R}, u, s)\right\}.$$
- *For any $\mathbf{a} \in R_q^{1\times \ell}$ with trapdoor $\mathbf{R}$, any matrix $\mathbf{a}'^t \in R_q^{1\times h}$ and any $s \geq C_{1,r} \cdot \sqrt{s_1(\mathbf{R})^2 + 1} \cdot \omega(\sqrt{\log \ell n})$, $\mathsf{DelTrapR}([\mathbf{a}^t \mid \mathbf{a}'^t], \mathbf{R}, s)$ outputs a trapdoor $\mathbf{R}' \in R_q^{\ell\times h}$ for $[\mathbf{a}^t \mid \mathbf{a}'^t]$ with distribution independent of $\mathbf{R}$ and $s_1(\mathbf{R}') \leq C_{0,r} \cdot s\sqrt{n} \cdot (\sqrt{\ell} + \sqrt{h} + \omega(\sqrt{\log n}))$. Further, for $s \geq \omega(\sqrt{\log \ell n})$ and under the same conditions, the following distributions are statistically close:*
$$\left\{(\mathbf{a}^t, \mathbf{a}'^t, \mathbf{R}') \middle| \begin{array}{c}(\mathbf{a}^t, \mathbf{R}) \leftarrow \mathsf{GenTrapR}(1^n, 1^\ell, s, q), \mathbf{a}'^t \xleftarrow{\$} R_q^{1\times h}, \\ \mathbf{R}' \leftarrow \mathsf{DelTrapR}([\mathbf{a}^t \mid \mathbf{a}'^t], \mathbf{R}, s)\end{array}\right\}$$
and
$$\left\{(\mathbf{a}^t, \mathbf{a}'^t, \mathbf{R}') \middle| (\mathbf{a}^t, \mathbf{R}) \leftarrow \mathsf{GenTrapR}(1^n, 1^\ell, s, q), \mathbf{R}' \leftarrow D_{R,s}^{\ell\times h}, \mathbf{a}'^t := \mathbf{a}^t\mathbf{R}' + \mathbf{g}^t\right\}.$$

Finally, we present the RSIS assumption.

Definition 6 (Ring Short Integer Solution Assumption (RSIS)). *Let $\lambda \in \mathbb{N}, n = n(\lambda) = 2^k$ for a $k = k(\lambda)$, $\ell = \ell(\lambda), \beta = \beta(\lambda) \in \mathbb{N}$ and $q = q(n)$. We say that the $\mathsf{RSIS}_{n,\ell,q,\beta}$ assumption holds, if for every PPT algorithm $\mathcal{A}$ the following advantage is negligible in λ:*
$$\mathsf{Adv}_{\mathcal{A}}^{\mathsf{RSIS}_{n,\ell,q,\beta}}(\lambda) := \Pr\left[\mathbf{a}^t\mathbf{z} = 0 \wedge \mathbf{z} \neq \mathbf{0} \wedge \|\mathbf{z}\| \leq \beta \mid \mathbf{a}^t \xleftarrow{\$} R_q^{1\times \ell}, \mathbf{z} \leftarrow \mathcal{A}(\mathbf{a}^t)\right].$$

Restricting n to be a power of 2 and using the coefficient embedding $\mathfrak{cf}$ to define norms is a special case of the more general ring setting. For worst-case to average-case reductions similar to the plain SIS assumption, see [42,49,43].

5.2 Construction

Now we can present our scheme $\mathsf{IBS}_{\mathsf{RSIS}}$. It makes use of parameters $n = 2^k \in \Theta(\lambda)$ and $q = 3^h$ as above, $\ell \geq 2\lceil \log q \rceil + 3, \beta > 0$ and Gaussian parameters $s_0, s, s', s'', \tilde{s} \geq \omega(\sqrt{\log \ell n})$. Note that the parameters $\beta, \tilde{s}$ are only used in the security proof. In particular, this allows us to apply Lem. 7 to 11. To apply Lem. 12 and to make our reduction work, we need

$$
\begin{aligned}
s &\geq C_{1,r}\sqrt{s_0^2 {C_{0,r}}^2 \cdot n \cdot (\sqrt{\ell - h} + \sqrt{h} + \omega(\sqrt{\log n}))^2 + 1} \cdot \omega(\sqrt{\log \ell n}) \\
s' &\geq C_{1,r}\sqrt{s^2 {C_{0,r}}^2 \cdot n \cdot (\sqrt{\ell} + \sqrt{h} + \omega(\sqrt{\log n}))^2 + 1} \cdot \omega(\sqrt{\log \ell n}) \\
s'' &\geq C_{1,r}\sqrt{s'^2 {C_{0,r}}^2 \cdot n \cdot (\sqrt{\ell + h} + \sqrt{h} + \omega(\sqrt{\log n}))^2 + 1} \cdot \omega(\sqrt{\log \ell n}) \\
\beta &\geq (1 + 2C_{0,r}\tilde{s}\sqrt{n}(\sqrt{\ell} + \sqrt{h} + \omega(\sqrt{\log n})))s''\sqrt{\ell + 2h}.
\end{aligned}
$$

The scheme is presented in Fig. 8. As we already translated all lemmas needed for analysis to the ring setting, the final completeness and security proofs are a direct translation of the proofs in Section 4.

Alg $\mathsf{Setup}(1^\lambda)$
set parameters as in the text.
$(\mathbf{a}^t, \mathbf{T}) \leftarrow \mathsf{GenTrapR}(1^n, 1^\ell, s_0, q)$
$\mathsf{mpk} := \mathbf{a}^t \in R_q^{1\times\ell}, \mathsf{msk} := \mathbf{T}$
return $(\mathsf{mpk}, \mathsf{msk})$

Alg $\mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$
$\mathbf{h}_1^t \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
$\mathbf{f}_{\mathsf{id}}^t := [\mathbf{a}^t \mid \mathbf{h}_1^t] \in R_q^{1\times(\ell+h)}$
$\mathbf{T}_{\mathsf{id}} \leftarrow \mathsf{DelTrapR}(\mathbf{f}_{\mathsf{id}}^t, \mathbf{T}, s)$
return $\mathsf{sk}_{\mathsf{id}} := \mathbf{T}_{\mathsf{id}}$

Alg $\mathsf{Sig}(\mathsf{sk}_{\mathsf{id}}, \mathsf{m})$
$\mathbf{h}_1^t \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id}), \mathbf{h}_2^t \leftarrow \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$
$\mathbf{f}_{\mathsf{id},\mathsf{m}}^t := [\mathbf{a}^t \mid \mathbf{h}_1^t \mid \mathbf{h}_2^t] \in R_q^{1\times(\ell+2h)}$
$\mathbf{T}_{\mathsf{id},\mathsf{m}} \leftarrow \mathsf{DelTrapR}(\mathbf{f}_{\mathsf{id},\mathsf{m}}^t, \mathbf{T}_{\mathsf{id}}, s')$
$\mathbf{z} \leftarrow \mathsf{SampleDR}(\mathbf{f}_{\mathsf{id},\mathsf{m}}^t, \mathbf{T}_{\mathsf{id},\mathsf{m}}, 0, s'')$
return $\sigma := \mathbf{z}$

Alg $\mathsf{Ver}(\mathsf{mpk}, \mathsf{m}, \mathbf{z})$
$\mathbf{h}_1^t \leftarrow \mathsf{H}_1(\mathsf{mpk}, \mathsf{id}), \mathbf{h}_2^t \leftarrow \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$
$\mathbf{f}_{\mathsf{id},\mathsf{m}}^t := [\mathbf{a}^t \mid \mathbf{h}_1^t \mid \mathbf{h}_2^t] \in R_q^{1\times(\ell+2h)}$
if $\mathbf{z} = \mathbf{0} \vee \mathbf{f}_{\mathsf{id},\mathsf{m}}^t \mathbf{z} \neq 0$: **return** 0
return $\|\mathbf{z}\| \leq s''\sqrt{(\ell + 2h)n}$

Fig. 8. The identity-based signature scheme $\mathsf{IBS}_{\mathsf{RSIS}} = (\mathsf{Setup}, \mathsf{KeyExt}, \mathsf{Sig}, \mathsf{Ver})$, where $\mathsf{H}_1 : \{0,1\}^* \to R_q^{1\times h}, \mathsf{H}_2 : \{0,1\}^* \to R_q^{1\times h}$ are random oracles.

Lemma 13. *The identity-based signature scheme* $\mathsf{IBS}_{\mathsf{RSIS}}$ *is* ρ*-complete, where* $\rho \geq 1 - \mathsf{negl}(\lambda)$.

Proof. Let $(\mathsf{mpk} = \mathbf{a}^t, \mathsf{msk} = \mathbf{T}) \in \mathsf{Setup}(1^\lambda)$ be a pair of key, let id be an identity and let m be a message. Further, let $\mathsf{sk}_{\mathsf{id}} \in \mathsf{KeyExt}(\mathsf{msk}, \mathsf{id})$ and $\mathbf{z} \in \mathsf{Sig}(\mathsf{sk}_{\mathsf{id}}, \mathsf{m})$ be a user secret key and a signature. By Lem. 12 the following hold with overwhelming probability: We have that $\mathsf{sk}_{\mathsf{id}} = \mathbf{T}_{\mathsf{id}}$ is a trapdoor for $\mathbf{f}_{\mathsf{id}}^t = [\mathbf{a}^t \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})]$, which is a prefix of $\mathbf{f}_{\mathsf{id},\mathsf{m}}^t = [\mathbf{a}^t \mid \mathsf{H}_1(\mathsf{mpk}, \mathsf{id}) \mid \mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})]$. Thus $\mathbf{T}_{\mathsf{id},\mathsf{m}}$ as used in $\mathsf{Sig}(\mathsf{sk}_{\mathsf{id}}, \mathsf{m})$ is a trapdoor for $\mathbf{f}_{\mathsf{id},\mathsf{m}}^t$, and the conditions of parameters. Further

Alg $\mathcal{B}(\mathbf{a}^t \in R_q^{1\times\ell})$

$(\mathcal{L}_{id}, \mathcal{L}_m, St) \leftarrow \mathcal{A}(1^\lambda)$
$\mathsf{mpk} := \mathbf{a}^t$
for $\mathsf{id} \in \mathcal{L}_{id}$:
  $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} \leftarrow D_{R,s}^{\ell\times h}$
  $h[1, \mathsf{mpk}, \mathsf{id}] := \mathbf{a}^t\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} + \mathbf{g}^t$
  $\mathsf{sk}_{\mathsf{id}} := \hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}$
  $\mathcal{L}_{sk} := \mathcal{L}_{sk} \cup \{\mathsf{sk}_{\mathsf{id}}\}$

for $(\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$:
  $\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} \leftarrow D_{R,s}^{\ell\times h}$
  $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] := \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} + \mathbf{g}^t$
  $\mathbf{b}^t := \mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$
  $\mathbf{c}^t := h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}]$
  $\mathbf{f}'^t_{\mathsf{id},\mathsf{m}} := [\mathbf{a}^t \mid \mathbf{c}^t \mid \mathbf{b}^t]$
  $\mathbf{f}^t_{\mathsf{id},\mathsf{m}} := [\mathbf{a}^t \mid \mathbf{b}^t \mid \mathbf{c}^t]$
  $\mathbf{T}'_{\mathsf{id},\mathsf{m}} \leftarrow \mathsf{DelTrapR}(\mathbf{f}'^t_{\mathsf{id},\mathsf{m}}, \mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}, s')$
  $\mathbf{z} \leftarrow \mathsf{SampleDR}(\mathbf{f}'^t_{\mathsf{id},\mathsf{m}}, \mathbf{T}'_{\mathsf{id},\mathsf{m}}, 0, s'')$
  $\mathbf{z}_{\mathsf{id},\mathsf{m}} := [\mathbf{z}_1^t \mid \mathbf{z}_3^t \mid \mathbf{z}_2^t]^t$
  $\mathcal{L}_{sig} := \mathcal{L}_{sig} \cup \{\mathbf{z}_{\mathsf{id},\mathsf{m}}\}$

$(\mathsf{id}^*, \mathsf{m}^*, \mathbf{z}^*) \leftarrow \mathcal{A}^{\mathsf{H}_1,\mathsf{H}_2}(St, \mathsf{mpk}, \mathcal{L}_{sk}, \mathcal{L}_{sig})$

if $\mathsf{id}^* \in \mathcal{L}_{id} \vee (\mathsf{id}^*, \mathsf{m}^*) \in \mathcal{L}_m$:
  return $\perp$
if $\mathbf{z}^* > s''\sqrt{(\ell+2h)n} \vee \mathbf{z}^* = \mathbf{0}$:
  return $\perp$
$\mathbf{b}^t := \mathbf{a}^t\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*}$
$\mathbf{c}^t := \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}$
$\mathbf{f}^t_{\mathsf{id}^*,\mathsf{m}^*} := [\mathbf{a}^t \mid \mathbf{b}^t \mid \mathbf{c}^t]$
if $\mathbf{f}^t_{\mathsf{id}^*,\mathsf{m}^*}\mathbf{z}^* \neq 0$: **return** $\perp$
$\mathbf{z} := [\mathbf{I}_\ell \mid \hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}^*$
return $\mathbf{z}$

Oracle $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id})$

if $h[1, \mathsf{mpk}, \mathsf{id}] = \perp$:
  $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} \leftarrow D_{R,\tilde{s}}^{\ell\times h}$
  $h[1, \mathsf{mpk}, \mathsf{id}] := \mathbf{a}^t\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}$
return $h[1, \mathsf{mpk}, \mathsf{id}]$

Oracle $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m})$

if $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] = \perp$:
  $\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} \leftarrow D_{R,\tilde{s}}^{\ell\times h}$
  $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}] := \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}$
return $h[2, \mathsf{mpk}, \mathsf{id}, \mathsf{m}]$

Fig. 9. Reduction $\mathcal{B}$, solving the RSIS problem using an adversary $\mathcal{A}$ against the UF-naCMA security of $\mathsf{IBS}_{\mathsf{RSIS}}$.

$\mathbf{z}$ is distributed statistically close to $D_{\Lambda_q^\perp(\mathbf{f}^t_{\mathsf{id},\mathsf{m}}),s''}$, which implies $\mathbf{f}^t_{\mathsf{id},\mathsf{m}}\mathbf{z} = \mathbf{0}$ and with overwhelming probability (by Lem. 10) $\|\mathbf{z}\| \leq s'' \cdot \sqrt{(\ell+2h)n}$, which makes Ver accept. □

Theorem 4. *The scheme* $\mathsf{IBS}_{\mathsf{RSIS}}$ *is an* UF-naCMA *secure identity-based signature scheme, under the* $\mathsf{RSIS}_{n,\ell,q,\beta}$ *assumption. In particular, for every* PPT *algorithm* $\mathcal{A}$ *there is a* PPT *algorithm* $\mathcal{B}$ *such that*

$$\mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{A},\mathsf{IBS}_{\mathsf{RSIS}}}(\lambda) \leq \mathsf{Adv}^{\mathsf{RSIS}_{n,\ell,q,\beta}}_{\mathcal{B}}(\lambda) + \mathsf{negl}(\lambda)$$

and $\mathbf{T}(\mathcal{B}) \approx \mathbf{T}(\mathcal{A})$.

Proof. The proof follows the corresponding proof in the plain SIS setting. We present a reduction $\mathcal{B}$ in Fig. 9 that solves the RSIS problem using an adversary $\mathcal{A}$ against the UF-naCMA security of $\mathsf{IBS}_{\mathsf{RSIS}}$. Note that the running time of $\mathcal{B}$ is dominated by the running time of $\mathcal{A}$. First, we argue that $\mathcal{B}$'s simulation is statistically close to the real security game and $\mathcal{A}$ can not notice $\mathcal{B}$'s barratries. As $s, \tilde{s}$ and ℓ are large enough, Lem. 8 implies that with overwhelming probability over $\mathbf{a}^t \xleftarrow{\$} R_q^\ell$ the distribution of $\mathbf{a}^t\mathbf{R}$ for $\mathbf{R} \leftarrow D_{R,\kappa}^{\ell\times h}, \kappa \in \{s, \tilde{s}\}$ is statistically close to uniform over $R_q^{1\times h}$, which implies that $\mathcal{B}$'s simulation of random oracle queries is statistically close to the real security game. Further Lem. 12 can be

used as follows. The distribution of user secret keys returned by $\mathcal{B}$ is statistically close to the distribution in the real game, by the last claim of Lem. 12 about $\mathsf{DelTrapR}$. Also, the way the random oracle is programmed by $\mathcal{B}$ implies that $\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}$ is a trapdoor for $[\mathbf{a}^t \mid \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} + \mathbf{g}^t]$. Thus, the second and third claim of Lem. 12 show that the signature output by $\mathcal{B}$ is statistically close to $D_{\Lambda_q^\perp(\mathbf{f}^t_{\mathsf{id},\mathsf{m}}),s''}$, as honest signatures are. Second, we argue that $\mathcal{B}$ can solve the RSIS problem with overwhelming probability, conditioned on $\mathcal{A}$'s success. To this end, we have to argue that $\mathbf{z}$ is a short non-zero vector that satisfies $\mathbf{a}^t\mathbf{z} = 0 \in R_q$. If $(\mathsf{id}^*, \mathsf{m}^*, \mathbf{z}^*)$ is a valid forgery, then $\mathsf{id}^* \notin \mathcal{L}_{id}$ and $(\mathsf{id}^*, \mathsf{m}^*) \notin \mathcal{L}_m$, which implies that

$$0 = \mathbf{f}^t_{\mathsf{id}^*,\mathsf{m}^*}\mathbf{z}^* = [\mathbf{a}^t \mid \mathbf{a}^t\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}^* = \mathbf{a}^t[\mathbf{I}_\ell \mid \hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}^*,$$

and thus $\mathbf{a}^t\mathbf{z} = 0$. Further note that $\mathbf{z}$ is short: By Lem. 7 we have that $s_1(\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*}), s_1(\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}) \leq C_{0,r} \cdot \tilde{s}\sqrt{n} \cdot (\sqrt{\ell} + \sqrt{h} + \omega(\sqrt{\log n}))$ with overwhelming probability. Hence

$$\begin{aligned}\|\mathbf{z}\| &\leq \|\mathbf{z}_1^*\| + \|[\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}_2^*\| \\ &\leq (1 + 2C_{0,r}\tilde{s}\sqrt{n}(\sqrt{\ell} + \sqrt{h} + \omega(\sqrt{\log n})))s''\sqrt{\ell + 2h} \leq \beta.\end{aligned}$$

Finally, $\mathbf{z} \neq \mathbf{0}$ can be seen as follows. Let $\mathbf{z}^* = [\mathbf{z}_1^* \mid \mathbf{z}_2^*]^t$ with $\mathbf{z}_1^* \in R_q^\ell, \mathbf{z}_2^* \in R_q^{2h}$. Then we have

$$\mathbf{z} = \mathbf{z}_1^* + [\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]\mathbf{z}_2^*.$$

If $\mathbf{z}_2^* = \mathbf{0}$, then $\mathbf{z} \neq \mathbf{0}$ as $\mathbf{z}_1^* \neq \mathbf{0}$. So we can assume that $\mathbf{z}_2^* \neq \mathbf{0}$ and in particular, that there is some non-zero component $z_{2,j}^* \neq 0, j \in [2h]$. Denote the columns of $[\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*} \mid \mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}]$ by $\mathbf{r}_i \in R_q^\ell, i \in [2h]$. Then $\mathbf{z} = \mathbf{0}$ implies that

$$-\frac{1}{z_{2,j}^*}(\mathbf{z}_1^* + \sum_{i \neq j} z_{2,i}^*\mathbf{r}_i) = \mathbf{r}_j.$$

The only information about $\mathbf{r}_j$ that $\mathcal{A}$ gets is a component of the hash value $\mathsf{H}_1(\mathsf{mpk}, \mathsf{id}^*) = \mathbf{a}^t\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}^*}$ (if $j \leq h$) or $\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}^*, \mathsf{m}^*) = \mathbf{a}^t\mathbf{R}_{\mathsf{mpk},\mathsf{id}^*,\mathsf{m}^*}$ (otherwise). Let $u \in R_q$ denote that component. Then from $\mathcal{A}$'s view, $\mathbf{r}_j$ is distributed as $D_{\Lambda_u^\perp(\mathbf{a}^t),s}$. This distribution has a large min-entropy (with overwhelming probability over $\mathbf{a}^t \xleftarrow{\$} R_q^{1\times\ell}$) by Lem. 11. To be more precise, setting $\mathbf{v}^t := (1, 0, \ldots, 0) \in R^\ell$, Lem. 11 states that the min-entropy of the first component of $\mathbf{r}_j$ is at least $\Omega(n)$. The entropy of the entire $\mathbf{r}_j$ can not be smaller than that. Hence the probability that $\mathbf{z} = \mathbf{0}$ is negligible, which finishes the proof. □

We will now give an example parameter instantiation. Here, we set $\ell := 3\log q$, note that $\omega(\sqrt{\log \ell n}) = \omega(\sqrt{\log n})$, and use the estimation that in every delegation the Gaussian width multiplies by $\sqrt{n} \cdot \omega(\sqrt{\log n})^2$, up to constants. Note that compared to the plain SIS setting, this is slightly worse, which results from the bound in Lem. 7 compared to Lem. 1. Further, we choose q to be a power of 3 with $n^a \leq q \leq n^{a+1}$ for some $a \in \mathbb{N}$. Then we obtain

$$\ell := 3\log q, \qquad s_0 := \tilde{s} := \omega(\sqrt{\log n}),$$

$$s := \hat{C} \cdot n^{1/2} \cdot \omega(\sqrt{\log m})^3, \qquad s' := \hat{C}^2 \cdot n \cdot \omega(\sqrt{\log m})^5,$$
$$s'' := \hat{C}^3 \cdot n^{3/2} \cdot \omega(\sqrt{\log m})^7, \qquad \beta := \tilde{C} \cdot n^2 \cdot \log(n)^{1/2} \cdot \omega(\sqrt{\log m})^9,$$

where $\hat{C} := \sqrt{2}C_{0,r}C_{1,r}$ and $\tilde{C} := 4\sqrt{5(a+1)}\hat{C}^3 C_{0,r}$ are constants such that the estimation is correct, and a is chosen such that $n^a \geq \beta \cdot \mathsf{poly}(n)$ and the worst-case to average-case reductions [42,49,43] apply. Let us summarize the key and signature sizes (in bits) of the non-adaptively secure scheme $\mathsf{IBE}_{\mathsf{RSIS}}$:

$$|\mathsf{mpk}| = \ell \cdot n\lceil\log(q)\rceil, \qquad |\mathsf{msk}| = (\ell - h) \cdot h \cdot n\lceil\log(q)\rceil,$$
$$|\mathsf{sk}_{\mathsf{id}}| = \ell \cdot h \cdot n\lceil\log(q)\rceil, \qquad |\sigma| = (\ell + 2h) \cdot n\lceil\log(q)\rceil.$$

Note that for our scheme based on plain SIS, we had quasi-quadratic key sizes and quasi-linear signature sizes, while for our scheme based on RSIS, all sizes are quasi-linear. However, we highlight that this comes at the cost of a more structured and hence stronger assumption.

6 Instantiation in the Quantum Random Oracle Model

We show how to prove our constructions tightly in the quantum random oracle model (QROM) [10]. Recall that the transformation from non-adaptive to adaptive security can be done with a chameleon hash (namely, without random oracles, cf. Section 3.1). Therefore it is sufficient to tightly prove security of our non-adaptively secure instantiations in Sections 4 and 5 in the QROM.

For the rest of this section, we focus only on the SIS setting. However, note that everything can be directly translated to the ring setting. First, recall that the reduction we use to show security programs the random oracles H_1 and H_2 as follows:

$$\mathsf{H}_1(\mathsf{mpk}, \mathsf{id}) := \begin{cases} \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}} + \mathbf{G}, & \text{if } \mathsf{id} \in \mathcal{L}_{id} \\ \mathbf{A}\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}, & \text{otherwise} \end{cases}$$
$$\mathsf{H}_2(\mathsf{mpk}, \mathsf{id}, \mathsf{m}) := \begin{cases} \mathbf{A}\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} + \mathbf{G}, & \text{if } (\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m \\ \mathbf{A}\mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}} & \text{otherwise} \end{cases}.$$

Here, $\mathcal{L}_{id}$ are the identities for which the adversary wants to see a user secret key and $\mathcal{L}_m$ are the pairs of identities and messages for which the adversary wants to see a signature. Furthermore, matrix $\mathbf{A}$ is the master public key and matrices $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}, \mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}$ are short Gaussian matrices. Also, note that the reduction programs the random oracles in this way before the adversary gets access to them. If we want to show that the proof goes through in the QROM, then we only have to argue that this programming can still be done without the adversary noticing. To do so, we need the following lemma which is Lemma 3 in [10].

Lemma 14. *Let $\mathcal{A}$ be a quantum algorithm with quantum oracle access to oracle O. Assume that $\mathcal{A}$ makes at most Q quantum oracle queries to O. Consider two instantiations of oracle O:*

- *O_0 is a quantum random oracle.*
- *O_1 is sampled from a distributions of functions, such that for each x in the domain $O_1(x)$ is identically and independently distributed according to a distribution $\mathcal{D}$ whose statistical distance is within ε from uniform (i.e. it is ε-close to uniform).*

Then for any input z, the statistical distance of $\mathcal{A}$'s output in input z with quantum oracle access to O_0 and $\mathcal{A}$'s output in input z with quantum oracle access to O_1 is at most $4Q^2\sqrt{\varepsilon}$.

To use this lemma, let Sam be an algorithm that takes uniformly random coins as input and outputs a matrix from the appropriate Gaussian distribution, i.e. a matrix distributed as the matrices $\hat{\mathbf{R}}_{\mathsf{mpk},\mathsf{id}}, \mathbf{R}_{\mathsf{mpk},\mathsf{id},\mathsf{m}}$ above.

We will now sketch a sequence of games, such that the first game is the security game **UF-naCMA** in which the adversary gets quantum access to random oracles H_1 and H_2 and the last game simulates the oracles as described above. Formally, these games are presented in Fig. 10. As said, the first game $\mathbf{G}_0$ is the security game **UF-naCMA**. In game $\mathbf{G}_1$, we let $\tilde{\mathsf{H}}_1$ be a random function and define

$$\mathsf{H}_1(\mathsf{mpk},\mathsf{id}) := \begin{cases} \tilde{\mathsf{H}}_1(\mathsf{mpk},\mathsf{id}) + \mathbf{G}, & \text{if } \mathsf{id} \in \mathcal{L}_{id} \\ \tilde{\mathsf{H}}_1(\mathsf{mpk},\mathsf{id}), & \text{otherwise} \end{cases}.$$

Note that H_1 is distributed exactly as before and hence the view of the adversary does not change. In the next game $\mathbf{G}_2$, we let $\bar{\mathsf{H}}_1$ be another random function and set

$$\mathsf{H}_1(\mathsf{mpk},\mathsf{id}) := \begin{cases} \mathbf{A} \cdot \mathsf{Sam}(\bar{\mathsf{H}}_1(\mathsf{mpk},\mathsf{id})) + \mathbf{G}, & \text{if } \mathsf{id} \in \mathcal{L}_{id} \\ \mathbf{A} \cdot \mathsf{Sam}(\bar{\mathsf{H}}_1(\mathsf{mpk},\mathsf{id})), & \text{otherwise} \end{cases}.$$

To see that the advantage of the adversary only changes by a negligible amount, note that we can apply Lem. 14 by setting oracle O_1 to be

$$\mathrm{O}_1(\mathsf{mpk},\mathsf{id}) := \mathbf{A} \cdot \mathsf{Sam}(\bar{\mathsf{H}}_1(\mathsf{mpk},\mathsf{id})).$$

The statistical distance ε to uniform is guaranteed to be negligible by Lem. 2. A similar sequence of games can be applied afterwards for the oracle H_2. We end up in game $\mathbf{G}_4$ where we can apply the same reduction we used in the classical random oracle model. In summary, we showed the following statement.

Theorem 5. *The scheme $\mathsf{IBS}_{\mathsf{SIS}}$ is an $\mathsf{UF\text{-}naCMA}$ secure identity-based signature scheme, under the $\mathsf{SIS}_{n,m,q,\beta}$ assumption in the quantum random oracle model. In particular, for every PPT algorithm $\mathcal{A}$ there is a PPT algorithm $\mathcal{B}$ such that*

$$\mathsf{Adv}^{\mathsf{UF\text{-}naCMA}}_{\mathcal{A},\mathsf{IBS}_{\mathsf{SIS}}}(\lambda) \leq \mathsf{Adv}^{\mathsf{SIS}_{n,m,q,\beta}}_{\mathcal{B}}(\lambda) + \mathsf{negl}(\lambda)$$

and $\mathbf{T}(\mathcal{B}) \approx \mathbf{T}(\mathcal{A})$.

Oracle $\mathsf{H}_1(\mathsf{mpk}', \mathsf{id})$ // $\mathbf{G}_0, \mathbf{G}_1$

01 **if** $\mathsf{mpk}' = \mathsf{mpk} \wedge \mathsf{id} \in \mathcal{L}_{id}$: **return** $\tilde{\mathsf{H}}_1(\mathsf{mpk}', \mathsf{id}) + \mathbf{G}$ // $\mathbf{G}_1$

02 **return** $\tilde{\mathsf{H}}_1(\mathsf{mpk}', \mathsf{id})$

Oracle $\mathsf{H}_1(\mathsf{mpk}', \mathsf{id})$ // $\mathbf{G}_2$-$\mathbf{G}_4$

03 **if** $\mathsf{mpk}' = \mathsf{mpk} \wedge \mathsf{id} \in \mathcal{L}_{id}$: **return** $\mathbf{A}\mathsf{Sam}(\bar{\mathsf{H}}_1(\mathsf{mpk}', \mathsf{id})) + \mathbf{G}$

04 **return** $\mathbf{A} \cdot \mathsf{Sam}(\bar{\mathsf{H}}_1(\mathsf{mpk}', \mathsf{id}))$

Oracle $\mathsf{H}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m})$ // $\mathbf{G}_0$-$\mathbf{G}_3$

05 **if** $\mathsf{mpk}' = \mathsf{mpk} \wedge (\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$: **return** $\tilde{\mathsf{H}}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m}) + \mathbf{G}$ // $\mathbf{G}_3$

06 **return** $\tilde{\mathsf{H}}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m})$

Oracle $\mathsf{H}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m})$ // $\mathbf{G}_4$

07 **if** $\mathsf{mpk}' = \mathsf{mpk} \wedge (\mathsf{id}, \mathsf{m}) \in \mathcal{L}_m$: **return** $\mathbf{A}\mathsf{Sam}(\bar{\mathsf{H}}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m})) + \mathbf{G}$

08 **return** $\mathbf{A}\mathsf{Sam}(\bar{\mathsf{H}}_2(\mathsf{mpk}', \mathsf{id}, \mathsf{m}))$

Fig. 10. The random oracles in the proof of $\mathsf{UF\text{-}naCMA}$ security of $\mathsf{IBS}_{\mathsf{SIS}}$ in the quantum random oracle model. Here, $\tilde{\mathsf{H}}_1\tilde{\mathsf{H}}_2 : \{0,1\}^* \to \mathbb{Z}_q^{n \times n\lceil \log q \rceil}$ and $\bar{\mathsf{H}}_1, \bar{\mathsf{H}}_2 : \{0,1\}^* \to \{0,1\}^\lambda$ are perfectly random functions. The adversary gets quantum access to these oracles. Lines or oracles with highlighted comments are only executed in the corresponding games.

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