Biometric Authentication: Formalization and Instantiation

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Abstract

Biometric authentication offers an error-tolerant approach to user verification. Despite its convenience, unlike traditional authentication methods, servers have to verify users' identities by comparing the similarity of enrolled and probed data instead of their equivalence. An authentication method based on comparing hashes of two templates thus fails. Additionally, unlike a user-defined password, biometrics reveal sensitive personal information and cannot be altered, raising significant privacy concerns. Furthermore, the inherent nature of biometrics data can introduce a non-negligible false positive rate. These issues make designing a biometric authentication scheme and analyzing its security challenging and highlight the importance of a rigorous study in this domain.

In this project, we explore these challenges of biometric authentication. We first formalize a biometric authentication scheme and propose security models for two security properties of interest: *unforgeability* and *indistinguishability*. Unforgeability refers to an adversary's ability to impersonate a user, while indistinguishability evaluates the server's knowledge of users' biometrics, related to privacy preservation. Subsequently, we analyze two existing instantiations of biometric authentication built on two cryptographic primitives: function-hiding inner product functional encryption and relational hash. Our results demonstrate conditions under which these schemes achieve security within out security model.

1 Preliminaries

In this project, we assume

- λ is the security parameter.
- $[m]$ denotes the set of integers $\{1, 2, \cdots, m\}$.
- $\mathbb{Z}_q$ is the finite field modulo a prime number q.
- A function $f(n)$ is called *negligible* iff for any integer c, $f(n) < \frac{1}{n^c}$ for all sufficiently large n. We write it as $f(n) = \mathsf{negl}$, and we may also use negl to represent an arbitrary negligible function.

- poly is the class of polynomial funcions. We may also use poly to represent an arbitrary polynomial function.
- We write sampling a value r from a distribution $\mathcal{D}$ as $r \leftarrow_\$ \mathcal{D}$. If S is a finite set, then $r \leftarrow_\$ S$ means sampling r uniformly from S.
- The distribution $\mathcal{D}^t$ denotes t identical and independent distributions of $\mathcal{D}$.
- A PPT algorithm denotes a probabilistic polynomial time algorithm. Unless otherwise specified, all algorithms run in PPT.

We introduce two primitives to instantiate a biometric authentication scheme: function-hiding inner product functional encryption and relatioanl hash.

Definition 1 (Function-Hiding Inner Product Functional Encryption)**.** A *function-hiding inner product functional encryption* (fh-IPFE) scheme FE for a field $\mathbb{F}$ and input length k is composed of PPT algorithms $\mathsf{FE.Setup}$, $\mathsf{FE.KeyGen}$, $\mathsf{FE.Enc}$, and $\mathsf{FE.Dec}$:

- $\mathsf{FE.Setup}(1^\lambda) \rightarrow \mathsf{msk}, \mathsf{pp}$: It outputs the public parameter pp and the master secret key msk.
- $\mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}) \rightarrow f_{\mathbf{x}}$: It generates the functional decryption key $f_{\mathbf{x}}$ for an input vector $\mathbf{x} \in \mathbb{F}^k$.
- $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y}) \rightarrow \mathbf{c}_{\mathbf{y}}$: It encrypts the input vector $\mathbf{y} \in \mathbb{F}^k$ to the ciphertext $\mathbf{c}_{\mathbf{y}}$.
- $\mathsf{FE.Dec}(\mathsf{pp}, f_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow z$: It outputs a value $z \in \mathbb{F}$ or an error symbol $\perp$.

Correctness: An fh-IPFE scheme FE is *correct* if $\forall(\mathsf{msk}, \mathsf{pp}) \leftarrow \mathsf{FE.Setup}(1^\lambda)$ and $\mathbf{x}, \mathbf{y} \in \mathbb{F}^k$, we have

$$\mathsf{FE.Dec}(\mathsf{pp}, \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}), \mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y})) = \mathbf{x}\mathbf{y}^T \in \mathbb{F}.$$

Instantiation using an fh-IPFE scheme is given in Section 2.1.

Definition 2 (Relational Hash (adapted from [MR14]))**.** Let R_λ be a relation over sets X_λ, Y_λ, and Z_λ. A *relational hash* scheme RH for R_λ consists of PPT algorithms $\mathsf{RH.KeyGen}$, $\mathsf{RH.HASH}_1$, $\mathsf{RH.HASH}_2$, and $\mathsf{RH.Verify}$:

- $\mathsf{RH.KeyGen}(1^\lambda) \rightarrow \mathsf{pk}$: It outputs a public hash key pk.
- $\mathsf{RH.Hash}_1(\mathsf{pk}, \mathbf{x}) \rightarrow \mathbf{h}_{\mathbf{x}}$: Given a hash key pk and $\mathbf{x} \in X_\lambda$, it outputs a hash $\mathbf{h}_{\mathbf{x}}$.
- $\mathsf{RH.Hash}_2(\mathsf{pk}, \mathbf{y}) \rightarrow \mathbf{h}_{\mathbf{y}}$: Given a hash key pk and $\mathbf{y} \in Y_\lambda$, it outputs a hash $\mathbf{h}_{\mathbf{y}}$.
- $\mathsf{RH.Verify}(\mathsf{pk}, \mathbf{h}_{\mathbf{x}}, \mathbf{h}_{\mathbf{y}}, \mathbf{z}) \rightarrow r \in \{0, 1\}$: Given a hash key pk, two hashes $\mathbf{h}_{\mathbf{x}}$ and $\mathbf{h}_{\mathbf{y}}$, and $\mathbf{z} \in Z_\lambda$, it verifies whether the relation among $\mathbf{x}, \mathbf{y}$ and $\mathbf{z}$ holds.

Correctness: A relational hash scheme RH is *correct* if $\forall \mathbf{x}, \mathbf{y}, \mathbf{z} \in X_\lambda \times Y_\lambda \times Z_\lambda$,

$$\Pr\left[\begin{array}{l} \mathsf{pk} \leftarrow \mathsf{RH.KeyGen}(1^\lambda) \\ \mathbf{h_x} \leftarrow \mathsf{RH.Hash}_1(\mathsf{pk}, \mathbf{x}) : \mathsf{RH.Verify}(\mathsf{pk}, \mathbf{h_x}, \mathbf{h_y}, \mathbf{z}) = R(\mathbf{x}, \mathbf{y}, \mathbf{z}) \\ \mathbf{h_y} \leftarrow \mathsf{RH.Hash}_2(\mathsf{pk}, \mathbf{y}) \end{array}\right] = 1 - \mathsf{negl}.$$

Note that Z_λ is an auxiliary input. When the relation R is over two sets $X \times Y$, we ignore Z and write $\mathsf{RH.Verify}(\mathsf{pk}, \mathbf{h_x}, \mathbf{h_y})$.

Instantiation using a relational hash is given in Section 2.2.

2 Formalization

In general, an authentication shceme Π associated with a family of biometric distributions $\mathbb{B}$ is composed of the following algorithms.

- $\mathsf{Setup}(1^\lambda) \rightarrow \mathsf{esk}, \mathsf{psk}, \mathsf{csk}$: It outputs the enrollment secret key esk, probe secret key psk, and compare secret key csk.
- $\mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \rightarrow \mathbf{b}$: Given an oracle $\mathcal{O}_\mathcal{B}$, which samples biometric data from the distribution $\mathcal{B} \in \mathbb{B}$, it outputs a biometric template $\mathbf{b}$ for enrollment.
- $\mathsf{Enroll}(\mathsf{esk}, \mathbf{b}) \rightarrow \mathbf{c_x}$: On input a biometric template $\mathbf{b}$, it encodes it into a vector $\mathbf{x}$ and outputs the enrollment message $\mathbf{c_x}$.
- $\mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}() \rightarrow \mathbf{b}'$: Given an oracle $\mathcal{O}_\mathcal{B}$, which samples biometric data from the distribution $\mathcal{B} \in \mathbb{B}$, it outputs a biometric template $\mathbf{b}'$ for probe.
- $\mathsf{Probe}(\mathsf{psk}, \mathbf{b}') \rightarrow \mathbf{c_y}$: On input a biometric template $\mathbf{b}'$, it encodes it into a vector $\mathbf{y}$ and outputs the probe message $\mathbf{c_y}$.
- $\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y}) \rightarrow s$: It compares the enrollment message $\mathbf{c_x}$ and probe message $\mathbf{c_y}$ and outputs a score s.
- $\mathsf{Verify}(s) \rightarrow r \in \{0, 1\}$: It is a deterministic algorithm that reads the comparison score s and determines whether this is a successful authentication $(r = 1)$ or not $(r = 0)$.

We also consider a deterministic algorithm $\mathsf{BioCompare}$ for authentication correctness.

- $\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}') \rightarrow s$: Given two biometric templates $\mathbf{b}$ and $\mathbf{b}'$, it outputs a score s.

Correctness: An authenticaion scheme Π is *correct* if for any biometric distributions $\mathcal{B}$ and $\mathcal{B}'$, let $\mathsf{esk}, \mathsf{psk}, \mathsf{csk} \leftarrow \mathsf{Setup}(1^\lambda)$, $\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$, $\mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}'}}()$, , $\mathbf{c_x} \leftarrow \mathsf{Enroll}(\mathsf{esk}, \mathbf{b})$, $\mathbf{c_y} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{b}')$. Then

$$\Pr\left[\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y}) = \mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')\right] = 1 - \mathsf{negl}.$$

2.1 Instantiation with an fh-IPFE Scheme

Let $\mathsf{FE} = (\mathsf{FE.Setup}, \mathsf{FE.KeyGen}, \mathsf{FE.Enc}, \mathsf{FE.Dec})$ be an fh-IPFE scheme we defined in Definition 1. Following [EM23], we can instantiate a biometric authentication scheme using FE with the distance metric the Euclidean distance. Let the biometric distribution $\mathcal{B} \subseteq [m]^k$, and let the associated field of FE be $\mathbb{Z}_q$ where q is a prime number larger than the maximum possible Euclidean distance $m^2 \cdot k$. The scheme is instantiated as follows.

- $\mathsf{Setup}(1^\lambda)$: It calls $\mathsf{FE.Setup}(1^\lambda) \to \mathsf{msk}, \mathsf{pp}$ and outputs $\mathsf{esk} \leftarrow (\mathsf{msk}, \mathsf{pp})$, $\mathsf{psk} \leftarrow (\mathsf{msk}, \mathsf{pp})$ and $\mathsf{csk} \leftarrow \mathsf{pp}$.
- $\mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$: It outputs a biometric template vector $\mathbf{b} \in [m]^k$.
- $\mathsf{Enroll}(\mathsf{esk}, \mathbf{b})$: On input a template vector $\mathbf{b} = (b_1, b_2, \cdots, b_k)$, the algorithm first encodes it as $\mathbf{x} = (x_1, x_2, \cdots, x_{k+2}) = (b_1, b_2, \cdots, b_k, 1, \|\mathbf{b}\|^2)$. Next, it calls $\mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}) \to f_\mathbf{x}$ and outputs $\mathbf{c_x} \leftarrow f_\mathbf{x}$.
- $\mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}()$: It outputs a biometric template vector $\mathbf{b}' \in [m]^k$.
- $\mathsf{Probe}(\mathsf{psk}, \mathbf{b}')$: On input a template vector $\mathbf{b}' = (b'_1, b'_2, \cdots, b'_k)$, the algorithm first encodes it as $\mathbf{y} = (y_1, y_2, \cdots, y_{k+2}) = (-2b'_1, -2b'_2, \cdots, -2b'_k, \|\mathbf{b}'\|^2, 1)$. Next, it calls $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y}) \to \mathbf{c_y}$ and outputs $\mathbf{c_y}$.
- $\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y})$: It calls $\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c_x}, \mathbf{c_y}) \to s$ and outputs the value s.
- $\mathsf{Verify}(s)$: If $\sqrt{s} \leq \tau$, a pre-defined threshold for comparing the closeness of two templates, then it outputs $r = 1$; otherwise, it outputs $r = 0$.
- $\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')$: It outputs $\|\mathbf{b} - \mathbf{b}'\|^2$.

By the correctness of the functional encryption scheme FE, we have

$$s = \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c_x}, \mathbf{c_y}) = \mathbf{x}\mathbf{y}^T = \sum_{i=1}^{k} -2b_i b'_i + \|\mathbf{b}\|^2 + \|\mathbf{b}'\|^2 = \|\mathbf{b} - \mathbf{b}'\|^2.$$

which is equal to $\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')$. Therefore, if two templates $\mathbf{b}$ and $\mathbf{b}'$ are close enough such that $\|\mathbf{b} - \mathbf{b}'\| \leq \tau$, the scheme results in $r = 1$, a successful authentication.

Instantiated with an fh-IPFE scheme in this way, the comparison secret key csk is public, and the enrollment secret key esk and probe secret key psk are the same. Anyone with access to the enrollment message $\mathbf{c_x}$ and either esk or psk can probe any (invalidly encoded) $\mathbf{y}' \in \mathbb{Z}_q^{k+2}$ and find $\mathbf{x}\mathbf{y}'^T$ to get partial or full information about the biometric template $\mathbf{b}$. Even if the adversary has no esk or psk, if it can sample ciphertexts $\mathbf{c_y}$ corresponding to some unknown random vectors $\mathbf{y}$, and if the field size q is not large enough, it can also find a forged $\mathbf{c}_{\mathbf{y}^*}$ such that $\mathbf{x}\mathbf{y}^{*T} \leq \tau$ with a non-negligible probability to impersonate the user by sampling many times offline.

A security analysis of this instantiation in our security model is given in Section 4.

2.2 Instantiation with a Relational Hash Scheme

Let $\mathsf{RH} = (\mathsf{RH.KeyGen}, \mathsf{RH.Hash}_1, \mathsf{RH.Hash}_2, \mathsf{RH.Verify})$ be a relational hash scheme we defined in Definition 2 for the relation R^τ of Hamming distance proximity parametrized by a constant τ.

$$R^\tau = \{(\mathbf{x}, \mathbf{y}) \mid \mathsf{HD}(\mathbf{x}, \mathbf{y}) \le \tau \wedge \mathbf{x}, \mathbf{y} \in \{0,1\}^k\}$$

Note that here we ignore the third parameter Z. Following [MR14], we can instantiate a biometric authentication scheme using RH. Let the biometric distribution $\mathcal{B} \subseteq \{0,1\}^k$.

- $\mathsf{Setup}(1^\lambda)$: It calls $\mathsf{RH.KeyGen}(1^\lambda) \to \mathsf{pk}$ and outputs $\mathsf{esk} \leftarrow \mathsf{pk}$, $\mathsf{psk} \leftarrow \mathsf{pk}$, and $\mathsf{csk} \leftarrow \mathsf{pk}$.
- $\mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$: It outputs a biometric template vector $\mathbf{b} \in \{0,1\}^k$.
- $\mathsf{Enroll}(\mathsf{esk}, \mathbf{b})$: Let $\mathbf{x} \leftarrow \mathbf{b}$. It calls $\mathsf{RH.Hash}_1(\mathsf{pk}, \mathbf{x}) \to \mathbf{h_x}$ and outputs $\mathbf{c_x} \leftarrow \mathbf{h_x}$.
- $\mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}()$: It outputs a biometric template vector $\mathbf{b}' \in \{0,1\}^k$.
- $\mathsf{Probe}(\mathsf{psk}, \mathbf{b}')$: Let $\mathbf{y} \leftarrow \mathbf{b}$. It calls $\mathsf{RH.Hash}_2(\mathsf{pk}, \mathbf{y}) \to \mathbf{h_y}$ and outputs $\mathbf{c_y} \leftarrow \mathbf{h_y}$.
- $\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y})$: It calls $\mathsf{RH.Verify}(\mathsf{pk}, \mathbf{h_x}, \mathbf{h_y}) \to s$ and outputs the value s.
- $\mathsf{Verify}(s)$: It direclty returns $r \leftarrow s$.
- $\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')$: It outputs 1 if $(\mathbf{b}, \mathbf{b}') \in R^\tau$.

By the correctness of the relational hash scheme RH, we have (except for a negligible probability),

$$r = 1 \Leftrightarrow (\mathbf{x}, \mathbf{y}) = (\mathbf{b}, \mathbf{b}') \in R^\tau \Leftrightarrow \mathsf{HD}(\mathbf{b}, \mathbf{b}') \le \tau$$

A security analysis of this instantiation in our security model is given in Section 5.

3 Security Games

To rigorously analyze the security of an authentication scheme, we simulate biometric distributions of users by assuming the existence of a family $\mathbb{B}$ of distributions. We require that all distributions in $\mathbb{B}$ are efficiently samplable and $\mathbb{B}$ has an excessively large size for a PPT adversary to enumerate. We then provide interfaces for all algorithms to interact with $\mathbb{B}$.

- $\mathsf{BioSamp}()$: Generate a random distribution $\mathcal{B}$ of $\mathbb{B}$. By this we mean providing either parameters of an efficiently samplable distribution or a PPT algorithm as the sampler. For simplicity, we write $\mathcal{B} \leftarrow \mathsf{BioSamp}()$ as $\mathcal{B} \leftarrow_\$ \mathbb{B}$.

- $\mathsf{BioDelete}(\mathcal{B})$: Delete $\mathcal{B}$ from $\mathbb{B}$. Consequently, no further access to $\mathsf{BioSamp}$ can derive $\mathcal{B}$. For simplicity, we write $\mathsf{BioDelete}(\mathcal{B})$ as $\mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$.

- $\mathsf{TempSamp}(\mathcal{B})$: Let $\mathcal{B}$ be a biometric distribution in $\mathbb{B}$. This algorithm samples a biometric template from $\mathcal{B}$. For simplicity, we write $\mathbf{b} \leftarrow \mathsf{TempSamp}(\mathcal{B})$ as $\mathbf{b} \leftarrow_{\$} \mathcal{B}$.

3.1 Unforgeability

To describe the unforgeability of an authentication scheme, we model the ability of an adversary who tries to impersonate a user. The adversary $\mathcal{A}$ is given auxiliary information option that depends on our threat model and tries to find a valid probe message $\tilde{\mathbf{z}}$. The whole game $\mathsf{UF}_{\Pi,\mathbb{B},\mathsf{option}}$ is defined in Algorithm 1.

Algorithm 1 $\mathsf{UF}_{\Pi,\mathbb{B},\mathsf{option}}(\mathcal{A})$

$\mathcal{B} \leftarrow_{\$} \mathbb{B}, \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$
$\mathsf{esk}, \mathsf{psk}, \mathsf{csk} \leftarrow \mathsf{Setup}(1^\lambda)$
$\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}}}()$
$\mathbf{c_x} \leftarrow \mathsf{Enroll}(\mathsf{esk}, \mathbf{b})$
$\tilde{\mathbf{z}} \leftarrow \mathcal{A}(\mathsf{option})$
if $\tilde{\mathbf{z}}$ is equal to any output of $\mathcal{O}_{\mathsf{Probe}}$ **then**
    return 0
end if
$s \leftarrow \mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \tilde{\mathbf{z}})$
return $\mathsf{Verify}(s)$

The auxiliary information option can be nothing or include $\mathbf{c_x}, \mathsf{esk}, \mathsf{psk}, \mathsf{csk}$ or the following oracles:

- $\mathcal{O}_{\mathcal{B}}$: It outputs a biometric sample $\mathbf{b} \leftarrow_{\$} \mathcal{B}$. This oracle and psk should not be given at the same time.

- $\mathcal{O}_{\mathsf{Enroll}}(\mathsf{esk}, \cdot)$: On input $\mathbf{b}'$, it outputs the enrollment message $\mathsf{Enroll}(\mathsf{esk}, \mathbf{b}')$.

- $\mathcal{O}_{\mathsf{Probe}}(\mathsf{psk}, \cdot)$: On input $\mathbf{b}'$, it outputs the probe message $\mathsf{Probe}(\mathsf{psk}, \mathbf{b}')$. If this oracle is given, we require the adversary to return a $\tilde{\mathbf{z}}$ that is not equal to any previous answer of $\mathcal{O}_{\mathsf{Probe}}$.

- $\mathcal{O}_{\mathsf{log}}(\mathsf{csk}, \mathbf{c_x}, \cdot)$: On input $\mathbf{b}'$, it first computes $\mathbf{c_z} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{b}')$ and outputs $\mathsf{Verify}(\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_z}))$.

- $\mathcal{O}'_{\mathsf{Enroll}}(\cdot)$: On input esk', it first samples $\mathbf{b}' \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ and outputs $\mathsf{Enroll}(\mathsf{esk}', \mathbf{b}')$.

- $\mathcal{O}'_{\mathsf{Probe}}(\cdot)$: On input psk', it first samples $\mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}}}()$ and outputs $\mathsf{Probe}(\mathsf{psk}', \mathbf{b}')$. This oracle and psk should not be given at the same time.

We define the advantage of an adversary $\mathcal{A}$ in the $\mathsf{UF}_{\Pi,\mathbb{B},\mathsf{option}}$ game of a scheme Π associated with a family $\mathbb{B}$ of distributions as

$$\mathbf{Adv}^{\mathsf{UF}}_{\Pi,\mathbb{B},\mathcal{A},\mathsf{option}} := \Pr[\mathsf{UF}_{\Pi,\mathbb{B},\mathsf{option}}(\mathcal{A}) \to 1]$$

An authentication scheme Π associated with a family $\mathbb{B}$ of distributions is called *option-unforgeable* (option-UF) if for any PPT adversary $\mathcal{A}$,

$$\mathbf{Adv}^{\mathsf{UF}}_{\Pi,\mathbb{B},\mathcal{A},\mathsf{option}} = \mathsf{negl}.$$

For the rest of this project, if the scheme, the family distribution, and the auxiliary information option are clear from context, we omit the subscript and write the game as $\mathsf{UF}(\mathcal{A})$. This abbreviation also holds for all other games.

3.2 Choice of option and True/False Positive Rates

In this section, we detail possibilities of the auxiliary information option in the $\mathsf{UF}_{\Pi,\mathbb{B},\mathsf{option}}$ game and rule out trivial attacks.

For a biometric distribution $\mathcal{B} \in \mathbb{B}$ and $\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$, define the *true positive rates* TP.

$$\begin{aligned}
\mathsf{TP}(\mathcal{B}, \mathbf{b}) &:= \Pr[\mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}() : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1] \\
\mathsf{TP}(\mathcal{B}) &:= \Pr\begin{bmatrix} \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}() \end{bmatrix} : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1 \\
&= \mathbb{E}_{\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()}[\mathsf{TP}(\mathcal{B}, \mathbf{b})] \\
\mathsf{TP} &:= \Pr\begin{bmatrix} \mathcal{B} \leftarrow_\$ \mathbb{B} \\ \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_\mathcal{B}}() \end{bmatrix} : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1 \\
&= \mathbb{E}_{\mathcal{B} \leftarrow_\$ \mathbb{B}}[\mathsf{TP}(\mathcal{B})]
\end{aligned}$$

For a biometric distribution $\mathcal{B} \in \mathbb{B}, \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ and $\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$, we also define the *false positive rates* FP.

$$\begin{aligned}
\mathsf{FP}(\mathbf{b}) &:= \Pr\begin{bmatrix} \mathcal{B}' \leftarrow_\$ \mathbb{B} \\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}'}}() \end{bmatrix} : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1 \\
\mathsf{FP}(\mathcal{B}) &:= \Pr\begin{bmatrix} \mathcal{B}' \leftarrow_\$ \mathbb{B} \\ \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}'}}() \end{bmatrix} : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1 \\
&= \mathbb{E}_{\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()}[\mathsf{FP}(\mathbf{b})] \\
\mathsf{FP} &:= \Pr\begin{bmatrix} \mathcal{B} \leftarrow_\$ \mathbb{B}, \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}, \mathcal{B}' \leftarrow_\$ \mathbb{B} \\ \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \\ \mathbf{b} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}'}}() \end{bmatrix} : \mathsf{Verify}(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}')) = 1 \\
&= \mathbb{E}_{\mathcal{B} \leftarrow_\$ \mathbb{B}}[\mathsf{FP}(\mathcal{B})]
\end{aligned}$$

Ideally, we hope TP to be close to 1 and FP to be negligible for any $\mathcal{B}$. However, due to the nature of biometrics, FP can be non-negligible. In the design of UF game, we need to prevent a trivial attack that leverages TP or FP when it is non-negligible.

If option includes $\mathcal{O}_\mathcal{B}$ and either psk or $\mathcal{O}_{\mathsf{Probe}}$, the adversary can enjoy a winning rate TP. Therefore, we rule out the case that option includes both psk and $\mathcal{O}_\mathcal{B}$, and we forbid the adversary from returning what $\mathcal{O}_{\mathsf{Probe}}$ returns.

If option has only psk or $\mathcal{O}_{\mathsf{Probe}}$, the UF adversary $\mathcal{A}$ in Algorithm 2 can still enjoy a winning rate FP, if we do not place any restriction on the adversary's answer. Therefore, we only consider psk in option when FP is non-negligible, and we restrict the adversary's answer when $\mathcal{O}_{\mathsf{Probe}}$ is given.

Algorithm 2 $\mathcal{A}(\mathsf{psk})$ (or $\mathcal{A}^{\mathcal{O}_{\mathsf{Probe}}}$)

```
1: B' ←$ 𝔹
2: b' ← getProbe^{O_B'}()
3: c_y ← Probe(psk, b')        ▷ or c_y ← O_Probe(b')
4: return c_y
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$1{:}\ \mathcal{B}' \leftarrow_\$ \mathbb{B}$
$2{:}\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}'}}()$
$3{:}\ \mathbf{c_y} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{b}') \quad \triangleright \text{ or } \mathbf{c_y} \leftarrow \mathcal{O}_{\mathsf{Probe}}(\mathbf{b}')$
$4{:}\ \textbf{return } \mathbf{c_y}$

3.3 Indistinguishable against Malicious Server (IND-MSV)

In the game of indistinguishability against a malicious server, we model the ability of an authentication server who tries to identify the user, which describes the privacy leakage of the scheme. The adversary $\mathcal{A}$ is given oracles to two biometric distributions $\mathcal{B}^{(0)}$ and $\mathcal{B}^{(1)}$, the comparison key csk, an enrollment message $\mathbf{c_x}$, and a list of t probe messages $\{\mathbf{c_y}^{(i)}\}_{i=1}^{t}$. It tries to guess from either $\mathcal{B}^{(0)}$ or $\mathcal{B}^{(1)}$ these messages are generated. The whole game is defined in Algorithm 3.

Algorithm 3 $\mathsf{IND\text{-}MSV}_{\Pi,\mathbb{B}}(\mathcal{A})$

$1{:}\ b \leftarrow_\$ \{0,1\}$
$2{:}\ \mathcal{B}^{(0)} \leftarrow_\$ \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}^{(0)}$
$3{:}\ \mathcal{B}^{(1)} \leftarrow_\$ \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}^{(1)}$
$4{:}\ \mathsf{esk}, \mathsf{psk}, \mathsf{csk} \leftarrow \mathsf{Setup}(1^\lambda)$
$5{:}\ \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}^{(b)}}}()$
$6{:}\ \mathbf{c_x} \leftarrow \mathsf{Enroll}(\mathsf{esk}, \mathbf{b})$
$7{:}\ \textbf{for } i = 1 \text{ to } t \textbf{ do}$
$8{:}\quad \mathbf{b}'^{(i)} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(b)}}}()$
$9{:}\quad \mathbf{c_y}^{(i)} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{b}'^{(i)})$
$10{:}\ \textbf{end for}$
$11{:}\ \tilde{b} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}^{(0)}}, \mathcal{O}_{\mathcal{B}^{(1)}}}(\mathsf{csk}, \mathbf{c_x}, \{\mathbf{c_y}^{(i)}\}_{i=1}^{t})$
$12{:}\ \textbf{return } 1_{\tilde{b}=b}$

We define the advantage of an adversary $\mathcal{A}$ in the $\mathsf{IND\text{-}MSV}$ game of a scheme

Π associated with a family of distributions $\mathbb{B}$ as

$$\mathbf{Adv}^{\mathsf{IND\text{-}MSV}}_{\Pi,\mathbb{B},\mathcal{A}} := \left|\Pr[\mathsf{IND\text{-}MSV}_{\Pi}(\mathcal{A}) \to 1] - \frac{1}{2}\right|.$$

An authentication scheme Π associated with a family $\mathbb{B}$ of distributions is called *indistinguishable against a malicious server (IND-MSV)* if for any PPT adversary $\mathcal{A}$,

$$\mathbf{Adv}^{\mathsf{IND\text{-}MSV}}_{\Pi,\mathbb{B},\mathcal{A}} = \mathsf{negl}.$$

4 Security Analysis: fh-IPFE-based Instantiation

Let Π be an authentication scheme instantiated by an fh-IPFE scheme FE as in Section 2.1. We discuss the UF and IND-MSV security of Π in this section. For this, we first define two security notions of FE.

Given an fh-IPFE scheme FE, we define the $\mathsf{fh\text{-}IND}$ game [EM23] in Algorithm 4.

Algorithm 4 $\mathsf{fh\text{-}IND}_{\mathsf{FE}}(\mathcal{A})$

1: $b \leftarrow_{\$} \{0,1\}$
2: $\mathsf{msk}, \mathsf{pp} \leftarrow \mathsf{FE.Setup}(1^\lambda)$
3: $\tilde{b} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathsf{KeyGen}}, \mathcal{O}_{\mathsf{Enc}}}(\mathsf{pp})$
4: **return** $1_{\tilde{b}=b}$

- $\mathcal{O}_{\mathsf{KeyGen}}(\cdot,\cdot)$: On input pair $(\mathbf{x}^{(0)}, \mathbf{x}^{(1)})$, it outputs $\mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}^{(b)})$.
- $\mathcal{O}_{\mathsf{Enc}}(\cdot,\cdot)$: On input pair $(\mathbf{y}^{(0)}, \mathbf{y}^{(1)})$, it outputs $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y}^{(b)})$.

To avoid trivial attacks, we consider *admissible adversaries.*

Definition 3 (Admissible Adversary)**.** Let $\mathcal{A}$ be an adversary in an $\mathsf{fh\text{-}IND}$ game, and let $(\mathbf{x}_1^{(0)}, \mathbf{x}_1^{(1)}), \cdots, (\mathbf{x}_{Q_K}^{(0)}, \mathbf{x}_{Q_K}^{(1)})$ be its queries to $\mathcal{O}_{\mathsf{KeyGen}}$ and $(\mathbf{y}_1^{(0)}, \mathbf{y}_1^{(1)}), \cdots, (\mathbf{y}_{Q_E}^{(0)}, \mathbf{y}_{Q_E}^{(1)})$ be its queries to $\mathcal{O}_{\mathsf{Enc}}$. We say $\mathcal{A}$ is *admissible* if $\forall i \in [Q_K], \forall j \in [Q_E]$,

$$\mathbf{x}_i^{(0)} {\mathbf{y}_j^{(0)}}^T = \mathbf{x}_i^{(1)} {\mathbf{y}_j^{(1)}}^T$$

Definition 4 (fh-IND Security)**.** An fh-IPFE scheme FE is called fh-IND secure if for any admissible adversary $\mathcal{A}$, the advantage of $\mathcal{A}$ in the $\mathsf{fh\text{-}IND}$ game in Algorithm 4 is

$$\mathbf{Adv}_{\mathsf{FE},\mathcal{A}}^{\mathsf{fh\text{-}IND}} := \left| \Pr[\mathsf{fh\text{-}IND}_{\mathsf{FE}}(\mathcal{A}) \to 1] - \frac{1}{2} \right| = \mathsf{negl}.$$

We note that the constructions in [DDM15; TAO16; Kim+16] are fh-IND secure.

We also define the RUF game in Algorithm 5 for a real number γ.

- $\mathcal{O}'_{\mathsf{KeyGen}}(\cdot)$: On input $\mathbf{x}'$, it outputs $\mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}')$.
- $\mathcal{O}'_{\mathsf{Enc}}(\cdot)$: On input $\mathbf{y}'$, it outputs $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y}')$. The adversary is required to return $\tilde{\mathbf{z}}$ that is not equal to any output of this oracle.

Definition 5 (RUF Security)**.** An fh-IPFE scheme FE is called RUF secure for a real number γ if for any adversary $\mathcal{A}$, the advantage of $\mathcal{A}$ in the RUF game in Algorithm 5 is

$$\mathbf{Adv}_{\mathsf{FE},\mathcal{A}}^{\mathsf{RUF},\gamma} := \Pr[\mathsf{RUF}_{\mathsf{FE}}^{\gamma}(\mathcal{A}) \to 1] = \mathsf{negl}.$$

Algorithm 5 $\mathsf{RUF}^{\gamma}_{\mathsf{FE}}(\mathcal{A})$

1: $\mathbf{r} \leftarrow_{\$} \mathbb{F}^k$
2: $\mathsf{msk}, \mathsf{pp} \leftarrow \mathsf{FE.Setup}(1^\lambda)$
3: $\mathbf{c} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{r})$
4: $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}'_{\mathsf{KeyGen}}, \mathcal{O}'_{\mathsf{Enc}}}(\mathsf{pp}, \mathbf{c})$
5: **if** $\tilde{\mathbf{z}}$ is equal to any output of $\mathcal{O}'_{\mathsf{Enc}}$ **then**
6: **return** 0
7: **end if**
8: $s \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \tilde{\mathbf{z}})$
9: **return** $1_{s \leq \gamma}$

We note that by adding a sEUF-CMA signature scheme $\mathsf{Sig} = (\mathsf{KeyGen}, \mathsf{Sign}, \mathsf{Verify})$, an fh-IPFE scheme can be upgraded to an RUF secure scheme. In a bit more detail, given any fh-IPFE FE, we construct the new scheme in the following way.

- $\mathsf{FE.Setup}$ also runs $\mathsf{Sig.KeyGen}(1^\lambda)$ and generates the signature secret key $\mathsf{sk}_{\mathsf{Sig}}$ and the verification public key $\mathsf{pk}_{\mathsf{Sig}}$. Let $\mathsf{sk}_{\mathsf{Sig}}$ be part of msk and $\mathsf{pk}_{\mathsf{Sig}}$ be part of pp.
- $\mathsf{FE.Enc}$ signs the encryption by $\mathsf{sk}_{\mathsf{Sig}}$.
- $\mathsf{FE.Dec}$ outputs the decryption if the verification succeeds. Otherwise, it outputs $\perp$.

If the adversary manages to find a $\tilde{\mathbf{z}}$ that is not equal to any output of $\mathcal{O}'_{\mathsf{Enc}}$ and $\mathsf{FE.Dec}$ on input $\tilde{\mathbf{z}}$ does not return $\perp$, the adversary is able to forge a valid signagure.

We note that RUF security is a new notion of an fh-IPFE scheme, and previous constructions do not definitely satisfy this property. We provide an example in [Che+21] and show that it is not RUF secure. Correspondingly, instantiation using this construction suffer attacks in the UF model.

4.1 UF Security

We first consider option-UF security when option includes $\mathcal{O}_{\mathsf{Enroll}}$. Note that in this instantiation, csk is the public parameter pp of FE and assumed to be given to all adversaries.

Theorem 1. *Let $\mathsf{option} = \{\mathbf{c}_{\mathbf{x}}, \mathsf{csk}, \mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\mathsf{Enroll}}\}$. For any distribution family $\mathbb{B}$, if FE is fh-IND secure and RUF secure for a $\gamma \geq \tau^2$, then Π is option-unforgeable.*

Proof. Given an adversary $\mathcal{A}$ in the $\mathsf{UF}_{\mathsf{option}}$ game, consider the reduction adversary $\mathcal{R}$ in Algorithm 6 which plays the $\mathsf{fh\text{-}IND}$ game. $\mathcal{R}$ runs $\mathcal{A}$ and simulates $\mathcal{O}_{\mathsf{Enroll}}(\mathsf{esk}, \mathbf{b}')$ by first encoding $\mathbf{b}' = (b'_1, \cdots, b'_k)$ into $\mathbf{x}' = (b'_1, \cdots, b'_k, 1, \|\mathbf{b}'\|^2)$ and calling $\mathcal{O}_{\mathsf{KeyGen}}(\mathbf{x}', \mathbf{x}')$ given in the $\mathsf{fh\text{-}IND}$ game. Note that since $\mathcal{R}$ never calls $\mathcal{O}_{\mathsf{Enc}}$, it is an admissible adversary.

Algorithm 6 $\mathcal{R}^{\mathcal{O}_{\mathsf{KeyGen}},\mathcal{O}_{\mathsf{Enc}}}(\mathsf{pp})$

1: $\mathcal{B} \leftarrow_\$ \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$
2: $\mathbf{b} = (b_1, \cdots, b_k) \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()$
3: $\mathbf{x} \leftarrow (b_1, \cdots, b_k, 1, \|\mathbf{b}\|^2)$
4: $\mathbf{r} \leftarrow_\$ \mathbb{F}^{k+2}$
5: $\mathbf{c} \leftarrow \mathcal{O}_{\mathsf{KeyGen}}(\mathbf{x}, \mathbf{r})$
6: $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_\mathcal{B},\mathcal{O}_{\mathsf{Enroll}}}(\mathbf{c}, \mathsf{pp})$
7: $s \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \tilde{\mathbf{z}})$
8: **if** $\mathsf{Verify}(s) = 1$ **then**
9:     **return** $\tilde{b} = 0$
10: **else**
11:     **return** $\tilde{b} \leftarrow_\$ \{0, 1\}$
12: **end if**

If the challenge bit $b = 0$, then $\mathcal{R}$ perfectly simulates a $\mathsf{UF}_{\mathsf{option}}$ game for $\mathcal{A}$. Therefore, the probability that $\mathsf{Verify}(s) = 1$ in Line 8 is $\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1]$.

For the case when the challenge bit $b = 1$, consider an adversary $\mathcal{A}'$ in Algorithm 7 in the RUF game. $\mathcal{A}'$ runs Line 1 and 6 of $\mathcal{R}$ and simulates $\mathcal{O}_{\mathsf{Enroll}}(\mathsf{esk}, \mathbf{b}')$ by first encoding $\mathbf{b}'$ into $\mathbf{x}'$ as before and calling $\mathcal{O}'_{\mathsf{KeyGen}}(\mathbf{x}')$ given in the RUF game.

Algorithm 7 $\mathcal{A}'^{\mathcal{O}'_{\mathsf{KeyGen}},\mathcal{O}'_{\mathsf{Enc}}}(\mathsf{pp}, \mathbf{c})$

$\mathcal{B} \leftarrow_\$ \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$
$\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_\mathcal{B},\mathcal{O}_{\mathsf{Enroll}}}(\mathbf{c}, \mathsf{pp})$
return $\tilde{\mathbf{z}}$

Now, if the challenge bit $b = 1$, then $\mathcal{R}$ perfectly simulates $\mathcal{A}'$ in the RUF game. The probability that $\mathsf{Verify}(s) = 1$, which is equivalent to $s \leq \tau^2$, in Line 8 is $\Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1]$

In conclusion, since $\gamma \geq \tau^2$,

$$
\begin{aligned}
\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] &= \Pr[b = 0] \cdot \left(\Pr[\mathsf{Verify}(s) = 1 \mid b = 0] + \frac{1}{2} \cdot \Pr[\mathsf{Verify}(s) = 0 \mid b = 0]\right) \\
&\quad + \Pr[b = 1] \cdot \frac{1}{2} \cdot \Pr[\mathsf{Verify}(s) = 0 \mid b = 1] \\
&= \frac{1}{2} + \frac{1}{4} (\Pr[\mathsf{Verify}(s) = 1 \mid b = 0] - \Pr[\mathsf{Verify}(s) = 1 \mid b = 1]) \\
&= \frac{1}{2} + \frac{1}{4} \left(\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] - \Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1]\right) \\
&\geq \frac{1}{2} + \frac{1}{4} (\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] - \Pr[\mathsf{RUF}^{\gamma}_{\mathsf{FE}}(\mathcal{A}') \to 1])
\end{aligned}
$$

Since both $\mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} = \left|\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] - \frac{1}{2}\right|$ and $\mathbf{Adv}^{\mathsf{RUF},\gamma}_{\mathsf{FE},\mathcal{A}'} = \Pr[\mathsf{RUF}^{\gamma}_{\mathsf{FE}}(\mathcal{A}') \to 1]$ are negligilbe,

$$
\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] \leq 4 \cdot \mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} + \mathbf{Adv}^{\mathsf{RUF},\gamma}_{\mathsf{FE},\mathcal{A}'} = \mathsf{negl}.
$$

□

For option that includes $\mathcal{O}_{\mathsf{Probe}}$, we first note that for any $d \in \mathbb{Z}_q$ and any nonzero vector $\mathbf{r} \in \mathbb{Z}_q^{k+2}$, there exists a vector $\mathbf{y} \in \mathbb{Z}_q^{k+2}$ such that $\mathbf{r}\mathbf{y}^T = d$.

Theorem 2. *Let option $= \{\mathbf{c}_{\mathbf{x}}, \mathsf{csk}, \mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\mathsf{Probe}}\}$. For any distribution family $\mathbb{B}$, if FE is fh-IND secure and RUF secure for a $\gamma \geq \tau^2$, then Π is option-unforgeable.*

Proof. Given an adversary $\mathcal{A}$ in the $\mathsf{UF}_{\mathsf{option}}$ game, consider the reduction adversary $\mathcal{R}$ in Algorithm 8 which plays the fh-IND game. $\mathcal{R}$ runs $\mathcal{A}$ and simulates $\mathcal{O}_{\mathsf{Probe}}$ in the following way.

- $\mathcal{O}_{\mathsf{Probe}}(\mathsf{psk}, \mathbf{b}')$: On input $\mathbf{b}' = (b'_1, \cdots, b'_k)$, it first encodes it as $\mathbf{y}' = (-2b'_1, \cdots, -2b'_k, \|\mathbf{b}'\|^2, 1)$. Next, it computes $d \leftarrow \mathbf{x}\mathbf{y}'^T$ and finds a vector $\mathbf{y}''$ such that $\mathbf{r}\mathbf{y}''^T = d$. Finally, it calls $\mathcal{O}_{\mathsf{Enc}}(\mathbf{y}', \mathbf{y}'')$, which is given by the fh-IND game, and returns the result.

Note that $(\mathbf{x}, \mathbf{r})$ is the only query of $\mathcal{R}$ to $\mathcal{O}_{\mathsf{KeyGen}}$, and for any query $(\mathbf{y}', \mathbf{y}'')$ to $\mathcal{O}_{\mathsf{Enc}}$, it satisfies $\mathbf{x}\mathbf{y}'^T = \mathbf{r}\mathbf{y}''^T$. Hence, $\mathcal{R}$ is an admissible adversary.

Algorithm 8 $\mathcal{R}^{\mathcal{O}_{\mathsf{KeyGen}}, \mathcal{O}_{\mathsf{Enc}}}(\mathsf{pp})$

1: $\mathcal{B} \leftarrow_\$ \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$
2: $\mathbf{b} = (b_1, \cdots, b_k) \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}}}()$
3: $\mathbf{x} \leftarrow (b_1, \cdots, b_k, 1, \|\mathbf{b}\|^2)$
4: $\mathbf{r} \leftarrow_\$ \mathbb{F}^{k+2}$
5: $\mathbf{c} \leftarrow \mathcal{O}_{\mathsf{KeyGen}}(\mathbf{x}, \mathbf{r})$
6: $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\mathsf{Probe}}}(\mathbf{c}, \mathsf{pp})$
7: **if** $\tilde{\mathbf{z}}$ is equal to any output of $\mathcal{O}_{\mathsf{Probe}}$ **then**
8:     **return** $\perp$
9: **end if**
10: $s \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \tilde{\mathbf{z}})$
11: **if** $\mathsf{Verify}(s) = 1$ **then**
12:     **return** $\tilde{b} = 0$
13: **else**
14:     **return** $\tilde{b} \leftarrow_\$ \{0, 1\}$
15: **end if**

If the challenge bit $b = 0$, then $\mathcal{R}$ perfectly simulates a $\mathsf{UF}_{\mathsf{option}}$ game for $\mathcal{A}$. Therefore, the probability that $\mathsf{Verify}(s) = 1$ in Line 11 is $\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1]$.

For the case when the challenge bit $b = 1$, consider an adversary $\mathcal{A}'$ in Algorithm 9 in the RUF game. $\mathcal{A}'$ runs $\mathcal{A}$ and simulates $\mathcal{O}_{\mathsf{Probe}}$ in the following way.

- $\mathcal{O}_{\mathsf{Probe}}(\mathsf{psk}, \mathbf{b}')$: It first encodes $\mathbf{b}'$ into $\mathbf{y}'$ as before. Next, it computes $d \leftarrow \mathbf{x}^{(*)}\mathbf{y}'^T$ and finds a vector $\mathbf{y}''$ such that $\mathbf{r}\mathbf{y}''^T = d$. Finally, it calls $\mathcal{O}'_{\mathsf{Enc}}(\mathbf{y}'')$, which is given by the RUF game, and returns the result.

To make $\mathcal{R}$ simulate $\mathcal{A}'$ in the RUF game, we still need to ensure two conditions.

Algorithm 9 $\mathcal{A}'^{\mathcal{O}'_{\mathsf{KeyGen}},\mathcal{O}'_{\mathsf{Enc}}}(\mathsf{pp}, \mathbf{c})$

$\mathcal{B} \leftarrow_{\$} \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$
$\mathbf{x}^{(*)} \leftarrow \mathsf{encodeEnroll}^{\mathcal{O}_\mathcal{B}}()$
Sample $k+2$ linearly independent vectors $\{\mathbf{e}^{(i)}\}_{i=1}^{k+2}$.
for $i = 1$ to $k+2$ **do**
    $\mathbf{c}^{(i)} \leftarrow \mathcal{O}'_{\mathsf{Enc}}(\mathbf{e}^{(i)})$.
    $d_i \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \mathbf{c}^{(i)})$.
end for
Find the vector $\mathbf{r}$ by solving the linear system $\{\mathbf{r}{\mathbf{e}^{(i)}}^T = d_i\}_{i=1}^{k+2}$.
if $\mathbf{r} = \mathbf{0}$ **then**
    return $\perp$
end if
$\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_\mathcal{B},\mathcal{O}_{\mathsf{Probe}}}(\mathbf{c}, \mathsf{pp})$
return $\tilde{\mathbf{z}}$

- $\mathbf{r} \neq \mathbf{0}$. Otherwise, $\mathcal{A}'$ cannot simulate $\mathcal{O}_{\mathsf{Probe}}$.
- $\tilde{\mathbf{z}} \neq \mathbf{c}^{(i)}$ for all i. The answers of $\mathcal{O}_{\mathsf{Probe}}$ have already been checked in $\mathcal{R}$.

Let $\mathcal{A}'$ play a tweaked $\mathsf{RUF}_{\mathsf{FE}}^{\tau^2}$ game which does not check that $\tilde{\mathbf{z}}$ is not equal to $\mathbf{c}^{(i)}$ for all i. That is, the game only checks whether $\tilde{\mathbf{z}}$ is not equal to any output of $\mathcal{O}'_{\mathsf{Enc}}$ called by $\mathcal{O}_{\mathsf{Probe}}$ of $\mathcal{A}$. Let the returned value of this game be V. We have Equation 1 and 2. The former one is a relation between $\mathcal{R}$ playing $\mathsf{fh\text{-}IND}$ game when the challenge bit $b = 1$ and V, and the other one is a relation between $\mathcal{A}'$ playing a regular $\mathsf{RUF}_{\mathsf{FE}}^{\tau^2}$ game and the tweaked one.

$$\Pr[\mathsf{Verify}(s) = 1 \mid b = 1 \land \mathbf{r} \neq \mathbf{0}] = \Pr[V = 1] \tag{1}$$

$$\Pr[\mathsf{RUF}_{\mathsf{FE}}^{\tau^2}(\mathcal{A}') \to 1] = \Pr\left[V = 1 \mid \bigwedge_{i=1}^{k+2} \tilde{\mathbf{z}} \neq \mathbf{c}^{(i)}\right] \tag{2}$$

For Equation 1, consider that

$$\begin{aligned}
\Pr[\mathsf{Verify}(s) = 1 \mid b = 1] &= \Pr[\mathsf{Verify}(s) = 1 \mid b = 1 \land \mathbf{r} \neq \mathbf{0}] \cdot \Pr[\mathbf{r} \neq \mathbf{0}] \\
&\quad + \Pr[\mathsf{Verify}(s) = 1 \mid b = 1 \land \mathbf{r} = \mathbf{0}] \cdot \Pr[\mathbf{r} = \mathbf{0}] \\
&\leq \Pr[V = 1] + \Pr[\mathbf{r} = 0] \\
&= \Pr[V = 1] + \frac{1}{q^{k+2}}
\end{aligned}$$

For Equation 2, consider that

$$\begin{aligned}
\Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1] &= \Pr\left[V = 1 \mid \bigwedge_{i=1}^{k+2} \tilde{\mathbf{z}} \neq \mathbf{c}^{(i)}\right] \\
&\geq \Pr[V = 1] - \Pr\left[\neg\left(\bigwedge_{i=1}^{k+2} \tilde{\mathbf{z}} \neq \mathbf{c}^{(i)}\right)\right] \\
&= \Pr[V = 1] - \Pr\left[\bigvee_{i=1}^{k+2} \tilde{\mathbf{z}} = \mathbf{c}^{(i)}\right] \\
&\geq \Pr[V = 1] - \sum_{i=1}^{k+2} \Pr[\tilde{\mathbf{z}} = \mathbf{c}^{(i)}].
\end{aligned}$$

Note that each $\mathbf{c}^{(i)} = \mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{e}^{(i)})$ for some uniform nonzero vector $\mathbf{e}^{(i)}$. Also note that distinct vectors in $\mathbb{Z}_q^{k+2}$ will have different encryptions due to the correctness of FE. Therefore, $\Pr[\tilde{\mathbf{z}} = \mathbf{c}^{(i)}] \leq \frac{1}{q^{k+2}-1}$ and

$$\Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1] \geq \Pr[V = 1] - \frac{k+2}{q^{k+2}-1}.$$

Combining both results from Equation 1 and 2, we derive

$$\Pr[\mathsf{Verify}(s) = 1 \mid b = 1] \leq \Pr[V = 1] + \frac{1}{q^{k+2}} \leq \Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1] + \frac{k+2}{q^{k+2}-1} + \frac{1}{q^{k+2}}.$$

Finally, similar to the proof of Theorem 1, we derive

$$\begin{aligned}
\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] &= \frac{1}{2} + \frac{1}{4}\left(\Pr[\mathsf{Verify}(s) = 1 \mid b = 0] - \Pr[\mathsf{Verify}(s) = 1 \mid b = 1]\right) \\
&\geq \frac{1}{2} + \frac{1}{4}\left(\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] - \Pr[\mathsf{RUF}^{\tau^2}_{\mathsf{FE}}(\mathcal{A}') \to 1] - \frac{k+2}{q^{k+2}-1} - \frac{1}{q^{k+2}}\right) \\
&\geq \frac{1}{2} + \frac{1}{4}\left(\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] - \Pr[\mathsf{RUF}^{\gamma}_{\mathsf{FE}}(\mathcal{A}') \to 1] - \frac{k+2}{q^{k+2}-1} - \frac{1}{q^{k+2}}\right)
\end{aligned}$$

Since both $\mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} = \left|\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] - \frac{1}{2}\right|$ and $\mathbf{Adv}^{\mathsf{RUF},\gamma}_{\mathsf{FE},\mathcal{A}'} = \Pr[\mathsf{RUF}^{\gamma}_{\mathsf{FE}}(\mathcal{A}') \to 1]$ are negligible,

$$\Pr[\mathsf{UF}_{\mathsf{option}}(\mathcal{A}) \to 1] \leq 4 \cdot \mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} + \mathbf{Adv}^{\mathsf{RUF},\gamma}_{\mathsf{FE},\mathcal{A}'} + \frac{k+2}{q^{k+2}-1} + \frac{1}{q^{k+2}} = \mathsf{negl}.$$

□

Unfortunately, for the instantiation in Section 2.1, we cannot achieve UF security when the adversary has psk, even if the false positive rate is negligible. The adversary can simply compute $\mathbf{c} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{0})$ and return $\mathbf{c}$. While in some fh-IPFE constructions [DDM15; Kim+16], $\mathsf{FE.Enc}$ disallows a zero input vector, the adversary can still compute $\mathbf{c} \leftarrow \mathsf{Probe}(\mathsf{psk}, \mathbf{v})$, where $\mathbf{v} = (0, \cdots, 0, 1, 0)$ has only a single 1 in the $k+1$-th coefficient, and win the game with probability 1. The same results also hold for option that includes esk since both psk and esk are equal to msk and allow the adversary to run $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{v})$ for any vector $\mathbf{v}$. We state this result formally in the following theorem.

Theorem 3. *Let option include esk or psk. For any distribution family $\mathbb{B}$ and functional encryption FE, Π is not option-unforgeable.*

4.2 IND-MSV Security

For the IND-MSV security, we first consider the following definition and assumption on the biometric distribution family $\mathbb{B}$.

Definition 6. For an authentication scheme Π, a distribution $\mathcal{B} \in \mathbb{B}$, and an integer t, define the distribution $\mathcal{D}_{\mathcal{B}}(t)$ as

$$\mathcal{D}_{\mathcal{B}}(t) = \left(\mathsf{BioCompare}(\mathbf{b}, \mathbf{b}^{(1)}), \mathsf{BioCompare}(\mathbf{b}, \mathbf{b}^{(2)}), \cdots, \mathsf{BioCompare}(\mathbf{b}, \mathbf{b}^{(t)})\right)$$

where $\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ and $\mathbf{b}^{(i)} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}}}()$ for all $i \in [t]$.

Assumption 1. Let t be an integer. Assume that for any two distributions $\mathcal{B}^{(0)}$ and $\mathcal{B}^{(1)}$ in the biometric distribution family $\mathbb{B}$, $\mathcal{D}_{\mathcal{B}^{(0)}}(t)$ and $\mathcal{D}_{\mathcal{B}^{(1)}}(t)$ are the same.

Note that indistinguishability between $\mathcal{D}_{\mathcal{B}^{(0)}}(t)$ and $\mathcal{D}_{\mathcal{B}^{(1)}}(t)$ is a necessary condition to achieve IND-MSV security because

$$\left(\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y}^{(1)}), \cdots, \mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \mathbf{c_y}^{(t)})\right) = \mathcal{D}_{\mathcal{B}^{(b)}}(t)$$

where b is the challenge bit.

Theorem 4. *For any distribution family $\mathbb{B}$ satisfying Assumption 1 and having a true positive rate $\mathsf{TP} > \frac{1}{\mathsf{poly}}$, if FE is fh-IND secure, then Π is IND-MSV secure.*

Proof. Given an adversary $\mathcal{A}$ in the $\mathsf{IND\text{-}MSV}$ game, consider the reduction adversary $\mathcal{R}$ in Algorithm 10 which plays the $\mathsf{fh\text{-}IND}$ game by running $\mathcal{A}$.
Note that $(\mathbf{x}^{(0)}, \mathbf{x}^{(1)})$ is the only query of $\mathcal{R}$ to $\mathcal{O}_{\mathsf{KeyGen}}$, and for any query $(\mathbf{y}^{(0)}, \mathbf{y}^{(1)})$ to $\mathcal{O}_{\mathsf{Enc}}$, it satisfies $\mathbf{x}^{(0)}{\mathbf{y}^{(0)}}^T = \mathbf{x}^{(1)}{\mathbf{y}^{(1)}}^T$. Hence, $\mathcal{R}$ is an admissible adversary.

The probability that Line 12 is satisfied is

$$\begin{aligned}
\Pr[\mathcal{D}_{\mathcal{B}^{(0)}}(1) = \mathcal{D}_{\mathcal{B}^{(1)}}(1)] &\geq \sum_{i=0}^{\tau} \Pr[\mathcal{D}_{\mathcal{B}^{(0)}}(1) = i]^2 \qquad \text{(Assumption 1)} \\
&\geq \frac{1}{\tau+1} \cdot \left(\sum_{i=0}^{\tau} \Pr[\mathcal{D}_{\mathcal{B}^{(0)}}(1) = i]\right)^2 \\
&= \frac{1}{\tau+1} \cdot \left(\Pr\left[\begin{matrix}\mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}^{(0)}}}() \\ \mathbf{b}' \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(0)}}}()\end{matrix} : \|\mathbf{b} - \mathbf{b}'\| \leq \tau\right]\right)^2 \\
&= \frac{\mathsf{TP}(\mathcal{B}^{(0)})^2}{\tau+1} = \frac{\mathsf{TP}^2}{\tau+1} \qquad \text{(Assumption 1)}
\end{aligned}$$

Algorithm 10 $\mathcal{R}^{\mathcal{O}_{\mathsf{KeyGen}},\mathcal{O}_{\mathsf{Enc}}}(\mathsf{pp})$

1: $\mathcal{B}^{(0)} \leftarrow_{\$} \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}^{(0)}$
2: $\mathcal{B}^{(1)} \leftarrow_{\$} \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}^{(1)}$
3: $\mathbf{b}^{(0)} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}^{(0)}}}(), \mathbf{x}^{(0)} \leftarrow (b_1^{(0)}, \cdots, b_k^{(0)}, 1, \|\mathbf{b}^{(0)}\|^2)$
4: $\mathbf{b}^{(1)} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}^{(1)}}}(), \mathbf{x}^{(1)} \leftarrow (b_1^{(1)}, \cdots, b_k^{(1)}, 1, \|\mathbf{b}^{(1)}\|^2)$
5: $\mathbf{c_x} \leftarrow \mathcal{O}_{\mathsf{KeyGen}}(\mathbf{x}^{(0)}, \mathbf{x}^{(1)})$
6: **for** $i = 1$ to t **do**
7: $\quad \mathbf{b}'^{(0)} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(0)}}}()$
8: $\quad \mathbf{y}^{(0)} \leftarrow (-2{b'_1}^{(0)}, \cdots, -2{b'_k}^{(0)}, \|\mathbf{b}'^{(0)}\|^2, 1)$
9: $\quad$ **repeat**
10: $\quad\quad \mathbf{b}'^{(1)} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(1)}}}()$
11: $\quad\quad \mathbf{y}^{(1)} \leftarrow (-2{b'_1}^{(1)}, \cdots, -2{b'_k}^{(1)}, \|\mathbf{b}'^{(1)}\|^2, 1)$
12: $\quad$ **until** $\mathbf{x}^{(0)}{\mathbf{y}^{(0)}}^T = \mathbf{x}^{(1)}{\mathbf{y}^{(1)}}^T$
13: $\quad {\mathbf{c_y}}^{(i)} \leftarrow \mathcal{O}_{\mathsf{Enc}}(\mathbf{y}^{(0)}, \mathbf{y}^{(1)})$
14: **end for**
15: $\tilde{b} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}^{(0)}},\mathcal{O}_{\mathcal{B}^{(1)}}}(\mathsf{pp}, \mathbf{c_x}, \{{\mathbf{c_y}}^{(i)}\}_{i=1}^t)$
16: **return** $\tilde{b}$

The expected number of repetitions is bounded above by $\frac{\tau+1}{\mathsf{TP}^2}$. Moreover, the probability that it is satisfied within T repetitions is at least

$$1 - (1 - \frac{\mathsf{TP}^2}{\tau+1})^T \geq 1 - e^{-T \cdot \frac{\mathsf{TP}^2}{\tau+1}}$$

We can reach a $1 - \mathsf{negl}$. probability that the loop will end within T times by setting a polynomial-size T.

Now, we show that $\mathcal{R}$ perfectly simulate an $\mathsf{IND\text{-}MSV}$ game for $\mathcal{A}$. If the challenge bit b of the $\mathsf{fh\text{-}IND}$ game is 0, $\mathbf{c_x}$ and ${\mathbf{c_y}}^{(i)}$ for all $i \in [t]$ are generated from $\mathcal{B}^{(0)}$ and have the same distributions as the inputs for an adversary in $\mathsf{IND\text{-}MSV}$ game. If the challenge bit b is 1, we show that distributions of $\mathbf{c_x}, \{{\mathbf{c_y}}^{(i)}\}_{i=1}^t$ also follow the same distribution given Assumption 1.

Let $b' \in \{0, 1\}$, define distributions

$$\mathbf{X}^{(b')} = \{\mathbf{b}^{(b')} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_{\mathcal{B}^{(b')}}}() : \mathbf{x}^{(b')} \leftarrow (b_1^{(b')}, \cdots, b_k^{(b')}, 1, \|\mathbf{b}^{(b')}\|^2)\}$$
$$\mathbf{Y}_i^{(b')} = \{\mathbf{b}^{(b')} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(b')}}}() : \mathbf{y}^{(b')} \leftarrow (-2b_1^{(b')}, \cdots, -2b_k^{(b')}, \|\mathbf{b}^{(b')}\|^2, 1)\}$$
$$\{\mathbf{Y}_i^{(b')}\}_{i \in [t]} = (\mathbf{Y}_1^{(b')}, \cdots, \mathbf{Y}_t^{(b')}) \qquad (t \text{ identical and independent distributions})$$

Let $\mathbf{Y}'_i$ be the distribution of $\mathbf{y}^{(1)}$ derived after the loop in Line 12 in the i-th iteration. For any $\{d_i\}_{i=1}^t, d_i > 0$,

$$\Pr\left[\bigwedge_{i=1}^t \mathbf{X}^{(0)}{\mathbf{Y}_i^{(0)}}^T = d_i^2\right] = \Pr\left[\mathcal{D}_{\mathcal{B}^{(0)}}(t) = (d_1, \cdots, d_t)\right]$$
$$= \Pr\left[\mathcal{D}_{\mathcal{B}^{(1)}}(t) = (d_1, \cdots, d_t)\right] = \Pr\left[\bigwedge_{i=1}^t \mathbf{X}^{(1)}{\mathbf{Y}_i^{(1)}}^T = d_i^2\right]$$

Hence, for any $\mathbf{x}$ and $\{\mathbf{y}_i\}_{i=1}^t$,

$$
\begin{aligned}
&\Pr[\mathbf{X}^{(1)} = \mathbf{x}, \mathbf{Y}'_1 = \mathbf{y}_1, \cdots, \mathbf{Y}'_t = \mathbf{y}_t] \\
&= \sum_{d_1,\cdots,d_t} \left(\Pr\left[\mathbf{X}^{(1)} = \mathbf{x}, \mathbf{Y}_1^{(1)} = \mathbf{y}_1, \cdots, \mathbf{Y}_t^{(1)} = \mathbf{y}_t \mid \bigwedge_{i=1}^{t} \mathbf{X}^{(1)} {\mathbf{Y}_i^{(1)}}^T = d_i^2 \right] \right. \\
&\qquad\qquad \left. \times \Pr\left[\bigwedge_{i=1}^{t} \mathbf{X}^{(0)} {\mathbf{Y}_i^{(0)}}^T = d_i^2 \right] \right) \\
&= \sum_{d_1,\cdots,d_t} \left(\Pr\left[\mathbf{X}^{(1)} = \mathbf{x}, \mathbf{Y}_1^{(1)} = \mathbf{y}_1, \cdots, \mathbf{Y}_t^{(1)} = \mathbf{y}_t \mid \bigwedge_{i=1}^{t} \mathbf{X}^{(1)} {\mathbf{Y}_i^{(1)}}^T = d_i^2 \right] \right. \\
&\qquad\qquad \left. \times \Pr\left[\bigwedge_{i=1}^{t} \mathbf{X}^{(1)} {\mathbf{Y}_i^{(1)}}^T = d_i^2 \right] \right) \\
&= \Pr[\mathbf{X}^{(1)} = \mathbf{x}, \mathbf{Y}_1^{(1)} = \mathbf{y}_1, \cdots, \mathbf{Y}_t^{(1)} = \mathbf{y}_t]
\end{aligned}
$$

which implies $\mathcal{R}$ also perfectly simulate an IND-MSV game for $\mathcal{A}$ when the challenge bit $b = 1$.

In conclusion,

$$\mathbf{Adv}_{\mathsf{FE},\mathcal{R}}^{\mathsf{fh\text{-}IND}} = \mathbf{Adv}_{\Pi,\mathbb{B},\mathcal{A}}^{\mathsf{IND\text{-}MSV}} = \mathsf{negl}.$$

which holds for all adversaries $\mathcal{A}$ in the IND-MSV game. This implies the IND-MSV security of Π.

□

5 Security Analysis: Relational Hash-based Instantiation

Let Π be an authentication scheme instantiated by a relational hash scheme RH as in Section 2.2. We discuss the UF and IND-MSV security of Π in this section. Note that in this instantiation, esk, psk, csk are all public hash keys pk of FE and assumed to be given to all adversaries.

Given a relational scheme RH for a relation $R \subseteq X \times Y$, we first define the unforgeability [MR14] of RH.

Definition 7 (Unforgeability)**.** A relational hash scheme RH is called *unforgeable* for the distribution $\mathcal{X}$ if for any adversary $\mathcal{A}$, the following probability is negligible.

$$\Pr\left[\begin{array}{l} \mathbf{x} \leftarrow_{\$} \mathcal{X} \\ \mathsf{pk} \leftarrow \mathsf{RH.KeyGen}(1^\lambda) \\ \mathbf{h_x} \leftarrow \mathsf{RH.Hash}_1(\mathsf{pk}, \mathbf{x}) \\ \tilde{\mathbf{z}} \leftarrow \mathcal{A}(\mathsf{pk}, \mathbf{h_x}) \end{array} : \mathsf{RH.Verify}(\mathsf{pk}, \mathbf{h_x}, \tilde{\mathbf{z}}) = 1\right] = \mathsf{negl}.$$

5.1 UF Security

We first consider option that includes $\mathbf{c_x}$.

Theorem 5. *Let* $\mathsf{option} = \{\mathbf{c_x}, \mathsf{esk}, \mathsf{psk}, \mathsf{csk}\}$. *If* RH *is unforgeable for the distribution*

$$\mathcal{X} = \{\mathcal{B} \leftarrow_\$ \mathbb{B} : \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \mid \mathbb{B}\}$$

, then Π *is* option*-unforgeable.*

In [MR14], the authors construct an RH that is unforgeable for the uniform distribution over $\{0,1\}^k$, under the hardness of some computational problems. Note that we need to provide knowledge of $\mathbb{B}$ in the distribution $\mathcal{X}$.

Proof. Recall that the distribution of $\mathbf{c_x}$ in the UF game of the instantiation of Section 2.2 is

$$\left\{\begin{array}{l}\mathcal{B} \leftarrow_\$ \mathbb{B} \\ \mathsf{pk} \leftarrow \mathsf{RH.KeyGen}(1^\lambda) \\ \mathbf{x} = \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}()\end{array} : \mathbf{c_x} \leftarrow \mathsf{RH.Hash}_1(\mathsf{pk}, \mathbf{x})\right\}$$

Also recall that $\mathsf{Verify}(\mathsf{Compare}(\mathsf{csk}, \mathbf{c_x}, \tilde{\mathbf{z}})) = \mathsf{RH.Verify}(\mathsf{pk}, \mathbf{c_x}, \tilde{\mathbf{z}})$. The option-UF security is thus guaranteed by the unforgeability of RH.

□

Remark As we mentioned in Section 3.2, an adversary with psk can enjoy a winning rate of the false positive rate FP of $\mathbb{B}$. Theorem 5 thus implies that if FP is not negligible, there does not exist an RH that is unforgeable for the distribution $\{\mathcal{B} \leftarrow_\$ \mathbb{B} : \mathbf{b} \leftarrow \mathsf{getEnroll}^{\mathcal{O}_\mathcal{B}}() \mid \mathbb{B}\}$.

Note that since $\mathsf{esk}, \mathsf{psk}$, and csk are all public in this instantiation, it is meaningless to discuss $\mathcal{O}_{\mathsf{Enroll}}, \mathcal{O}_{\mathsf{Probe}}$, or $\mathcal{O}_{\mathsf{log}}$. In addition, for option that includes $\mathcal{O}_\mathcal{B}$ or $\mathcal{O}'_{\mathsf{Probe}}$, as discussed in Section 3.2, we cannot achieve option-UF security since psk is public in this instantiation.

For option that includes $\mathcal{O}'_{\mathsf{Enroll}}$, we notice that for the RH construction in [MR14], there exists an invalid pk' such that $\mathsf{RH.Hash}_1(\mathsf{pk}', \mathbf{x})$ directly leaks $\mathbf{x}$. By returning $\mathsf{RH.Hash}_2(\mathsf{pk}, \mathbf{x})$, one can break the $\mathsf{UF}_{\mathsf{option}}$ game with probability 1.

5.2 IND-MSV Security

For the IND-MSV security, we have a negative result for Π.

Theorem 6. *For any distribution family* $\mathbb{B}$ *that* $\mathsf{TP} - \mathsf{FP} > \frac{1}{\mathsf{poly}}$, *and for any relational hash scheme* RH, Π *is not IND-MSV secure for any* $t \geq 0$.

Proof. Consider the adversary $\mathcal{A}$ in Algorithm 11. When the challenge bit $b = 0$, the probability that $\mathcal{A}$ wins is TP. When the challenge bit $b = 1$, the probability that $\mathcal{A}$ wins is $1 - \mathsf{FP}$. Now,

$$\mathbf{Adv}^{\mathsf{IND\text{-}MSV}}_{\Pi,\mathbb{B},\mathcal{A}} = \left|\Pr[\mathsf{IND\text{-}MSV}_\Pi(\mathcal{A}) \to 1] - \frac{1}{2}\right| = \left|\frac{1}{2}(\mathsf{TP} + 1 - \mathsf{FP}) - \frac{1}{2}\right| > \frac{1}{\mathsf{poly}}.$$

□

Algorithm 11 $\mathcal{A}^{\mathcal{O}_{\mathcal{B}^{(0)}},\mathcal{O}_{\mathcal{B}^{(1)}}}(\mathsf{csk}=\mathsf{pk},\mathbf{c_x},\{\mathbf{c_y}^{(i)}\}_{i=1}^{t})$

$\mathbf{y}^{(0)} = \mathbf{b}^{(0)} \leftarrow \mathsf{getProbe}^{\mathcal{O}_{\mathcal{B}^{(0)}}}()$
$\mathbf{h_y}^{(0)} \leftarrow \mathsf{RH.Hash}_2(\mathsf{pk},\mathbf{y}^{(0)})$
if $\mathsf{RH.Verify}(\mathsf{pk},\mathbf{c_x},\mathbf{h_y}^{(0)}) = 1$ **then**
  return 0
else
  return 1
end if

We note that this insecurity result holds whenever psk is public. When esk is public, one can also use $\mathbf{c_y}^{(i)}$ to verify from which distribution the chalenge ciphertexts are generated. We write this observation formally in the following theorem.

Theorem 7. *Given any distribution family $\mathbb{B}$ that $\mathsf{TP}-\mathsf{FP} > \frac{1}{\mathsf{poly}}$. If psk is public, Π is not IND-MSV secure for any $t \geq 0$. If esk is public, Π is not IND-MSV secure for any $t \geq 1$.*

6 Rough Ideas

Define the $\mathsf{RUF}_{\mathsf{FE}}^{\mathcal{O},\gamma}$ game in Algorithm 12 for a real number γ.

Algorithm 12 $\mathsf{RUF}_{\mathsf{FE}}^{\mathcal{O},\gamma}(\mathcal{A})$

1: $\mathbf{r} \leftarrow_{\$} \mathbb{F}^k$
2: $\mathsf{msk}, \mathsf{pp} \leftarrow \mathsf{FE.Setup}(1^\lambda)$
3: $\mathbf{c} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{r})$
4: $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}}(\mathsf{pp}, \mathbf{c})$
5: **if** $\tilde{\mathbf{z}}$ is equal to any output of $\mathcal{O}'_{\mathsf{Enc}}$ **then**
6:     **return** 0
7: **end if**
8: $s \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \tilde{\mathbf{z}})$
9: **return** $1_{s \le \gamma}$

The oracle $\mathcal{O}$ can be nothing or includes the following options based on the threat model.

- $\mathcal{O}'_{\mathsf{KeyGen}}(\cdot)$: On input $\mathbf{x}'$, it outputs $\mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x}')$.
- $\mathcal{O}'_{\mathsf{Enc}}(\cdot)$: On input $\mathbf{y}'$, it outputs $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{y}')$. The adversary is required to return $\tilde{\mathbf{z}}$ that is not equal to any output of this oracle.

Definition 8 (RUF Security)**.** An fh-IPFE scheme FE is called $\mathcal{O}$-RUF secure for a real number γ if for any adversary $\mathcal{A}$, the advantage of $\mathcal{A}$ in the $\mathsf{RUF}_{\mathsf{FE}}^{\mathcal{O},\gamma}$ game in Algorithm 5 is

$$\mathbf{Adv}_{\mathsf{FE},\mathcal{A}}^{\mathsf{RUF},\mathcal{O},\gamma} := \Pr[\mathsf{RUF}_{\mathsf{FE}}^{\mathcal{O},\gamma}(\mathcal{A}) \to 1] = \mathsf{negl}.$$

Theorem 8 (Theorem 1)**.** *Let* $\mathit{option} = \{\mathbf{c}_{\mathbf{x}}, \mathit{csk}, \mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\mathit{Enroll}}\}$*. For any distribution family* $\mathbb{B}$*, if* FE *is fh-IND secure and* $\mathcal{O}'_{\mathit{KeyGen}}$*-RUF secure for a* $\gamma \ge \tau^2$*, then* Π *is* option*-unforgeable.*

Theorem 9 (Theorem 2)**.** *Let* $\mathit{option} = \{\mathbf{c}_{\mathbf{x}}, \mathit{csk}, \mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\mathit{Probe}}\}$*. For any distribution family* $\mathbb{B}$*, if* FE *is fh-IND secure and* $\mathcal{O}'_{\mathit{Enc}}(\cdot)$*-RUF secure for a* $\gamma \ge \tau^2$*, then* Π *is* option*-unforgeable.*

Assumption 2. Let $\mathbf{x} \in \mathbb{F}^k, \mathbf{c} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x})$. Assume that $\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \mathbf{z})$ only returns when $\mathbf{z}$ corresponds to a *nonzero* vector $\mathbf{v} \in \mathbb{F}^k$. That is, assume that for any $\mathbf{z}$, there can only be two possibilities.

- There exists a vector $\mathbf{v} \in \mathbb{F}^k \backslash \{\mathbf{0}\}$ such that for any $\mathbf{x} \in \mathbb{F}^k, \mathbf{c} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x})$, and $\mathbf{c}_{\mathbf{v}} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{v})$,

$$\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \mathbf{z}) = \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \mathbf{c}_{\mathbf{v}}).$$

- For any $\mathbf{x} \in \mathbb{F}^k$ and $\mathbf{c} \leftarrow \mathsf{FE.KeyGen}(\mathsf{msk}, \mathsf{pp}, \mathbf{x})$, $\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \mathbf{z}) \to \perp$.

Note that this implies FE rejects zero vector $\mathbf{0}$ as the input of $\mathsf{FE.Enc}$.

Theorem 10. *Given Assumption 2. If FE is fh-IND secure, then FE is $\mathcal{O}'_{\mathsf{KeyGen}}$-RUF secure for any $\gamma \leq \|\mathbb{F}\|$.*

Proof. Given an adversary $\mathcal{A}$ in the $\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}$ game for any $\gamma < \|\mathbb{F}\|$. Let t be an integer, consider the reduction adversary $\mathcal{R}$. $\mathcal{R}$ simulates $\mathcal{O}'_{\mathsf{KeyGen}}(\mathbf{x}')$ by $\mathcal{O}_{\mathsf{KeyGen}}(\mathbf{x}', \mathbf{x}')$. If there exists an $s_i \neq \perp$ in Line 7, by Assumption 2, let $\tilde{\mathbf{z}}$ correspond to a vector $\tilde{\mathbf{v}}$.

Algorithm 13 $\mathcal{R}^{\mathcal{O}_{\mathsf{KeyGen}},\mathcal{O}_{\mathsf{Enc}}}(\mathsf{pp})$

1: $\mathbf{r}^{(0)}, \mathbf{r}^{(1)} \leftarrow_\$ \mathbb{F}^k$
2: $\mathbf{c} \leftarrow \mathcal{O}_{\mathsf{KeyGen}}(\mathbf{r}^{(0)}, \mathbf{r}^{(1)})$
3: $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}'_{\mathsf{KeyGen}}}(\mathsf{pp}, \mathbf{c})$
4: **for** $i = 1$ to t **do**
5:     $\mathbf{r}_i \leftarrow_\$ \mathbb{F}^k$
6:     $\mathbf{c}_i \leftarrow \mathcal{O}_{\mathsf{KeyGen}}(\mathbf{r}^{(0)}, \mathbf{r}_i)$
7:     $s_i \leftarrow \mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}_i, \tilde{\mathbf{z}})$
8: **end for**
9: **if** $\bigwedge_{i=1}^{t} s_i \leq \gamma$ **then**
10:     **return** $\tilde{b} = 0$
11: **else**
12:     **return** $\tilde{b} \leftarrow_\$ \{0, 1\}$
13: **end if**

If the challenge bit $b = 0$, then by Assumption 2, any $s_i \neq \perp$ in Line 7 implies all $s_i \neq \perp$ and $s_i = s_j$ for any i, j. Therefore, the probability that all $s_i \leq \gamma$ in Line 9 is

$$\begin{aligned}
\Pr\left[\bigwedge_{i=1}^{t} s_i \leq \gamma \mid b = 0\right] &= \Pr\left[s_1 \neq \perp \mid b = 0\right] \cdot \Pr\left[s_1 \leq \gamma \mid b = 0 \wedge s_1 \neq \perp\right] \\
&= \Pr\left[s_1 \neq \perp \mid b = 0\right] \cdot \Pr\left[\mathbf{r}^{(0)} \tilde{\mathbf{v}}^T \leq \gamma \mid b = 0 \wedge s_1 \neq \perp\right] \\
&= \Pr\left[s_1 \neq \perp \mid b = 0\right] \cdot \Pr\left[\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c}, \tilde{\mathbf{z}}) \leq \gamma \mid b = 0 \wedge s_1 \neq \perp\right] \\
&= \Pr\left[s_1 \neq \perp \mid b = 0\right] \cdot \Pr\left[\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}(\mathcal{A}) \to 1 \mid b = 0 \wedge s_1 \neq \perp\right] \\
&= \Pr\left[\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}(\mathcal{A}) \to 1\right]
\end{aligned}$$

If the challenge bit $b = 1$, for any $i \in [t]$,

$$\begin{aligned}
\Pr[s_i \leq \gamma \mid b = 1] &= \Pr[s_i \neq \perp \mid b = 1] \cdot \Pr[s_i \leq \gamma \mid b = 1 \wedge s_i \neq \perp] \\
&= \Pr[s_i \neq \perp \mid b = 1] \cdot \Pr[\mathbf{r}_i \tilde{\mathbf{v}}^T \leq \gamma \mid b = 1 \wedge s \neq \perp]
\end{aligned}$$

Note that $\mathbf{r}_i$ is independent of $\tilde{\mathbf{z}}$ and thus independent of $\tilde{\mathbf{v}}$. Hence, $\Pr[\mathbf{r}_i \tilde{\mathbf{v}}^T \leq \gamma \mid b = 1 \wedge s_i \neq \perp] = \frac{\gamma}{\|\mathbb{F}\|}$ and

$$\Pr\left[\bigwedge_{i=1}^{t} s_i \leq \gamma \mid b = 1\right] = \Pr\left[\bigwedge_{i=1}^{t} s_i \neq \perp \mid b = 1\right] \cdot \left(\frac{\gamma}{\|\mathbb{F}\|}\right)^t \leq \left(\frac{\gamma}{\|\mathbb{F}\|}\right)^t$$

In conclusion,

$$\begin{aligned}
\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] &= \frac{1}{2} + \frac{1}{4}\left(\Pr\left[\bigwedge_{i=1}^{t} s_i \le \gamma \mid b = 0\right] - \Pr\left[\bigwedge_{i=1}^{t} s_i \le \gamma \mid b = 1\right]\right) \\
&\ge \frac{1}{2} + \frac{1}{4}\left(\Pr[\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}(\mathcal{A}) \to 1] - \left(\frac{\gamma}{\|\mathbb{F}\|}\right)^t\right) \\
&\ge \frac{1}{2} + \frac{1}{4}\left(\Pr[\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}(\mathcal{A}) \to 1] - e^{-t\cdot(1-\frac{\gamma}{\|\mathbb{F}\|})}\right)
\end{aligned}$$

Take t be any integer larger than $\frac{\lambda}{1-\frac{\gamma}{\|\mathbb{F}\|}}$. Since $\mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} = \left|\Pr[\mathsf{fh\text{-}IND}(\mathcal{R}) \to 1] - \frac{1}{2}\right|$ and $e^{-t\cdot(1-\frac{\gamma}{\|\mathbb{F}\|})} \le e^{-\lambda}$ are negligible,

$$\Pr[\mathsf{RUF}^{\mathcal{O}'_{\mathsf{KeyGen}},\gamma}(\mathcal{A}) \to 1] \le e^{-t\cdot(1-\frac{\gamma}{\|\mathbb{F}\|})} + 4 \cdot \mathbf{Adv}^{\mathsf{fh\text{-}IND}}_{\mathsf{FE},\mathcal{R}} = \mathsf{negl}.$$

$\square$

7 Agenda

1. If an fh-IPFE scheme FE is fh-IND secure, by our current definition, sampling a $\mathbf{c_v}$ that corresponds to $\mathsf{FE.Enc}(\mathsf{msk}, \mathsf{pp}, \mathbf{v})$ of a random $\mathbf{v}$ and $\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c_x}, \mathbf{c_v})$ always returns is *impossible*. However, it is *possible* [DDM15; TAO16; Kim+16] if we allow decryption to return $\perp$ on most $\mathbf{x}, \mathbf{y} \in \mathbb{F}^k$.

2. I looked at some fh-IPFE constructions.

   (a) In [DDM15; TAO16; Kim+16]
   - The field size $|\mathbb{F}| = |\mathbb{Z}_q| = q$ is of exponential size of λ.
   - The decryption relies on finding $\langle \mathbf{x}, \mathbf{y} \rangle$ from $g^{\langle \mathbf{x}, \mathbf{y} \rangle}$ for a group generator g of order q. Discrete logarithm is hard. $\mathsf{FE.Dec}$ works only when $\langle \mathbf{x}, \mathbf{y} \rangle$ ranges in a pre-defined polynomial-size set.
   - [DDM15; TAO16] are fh-IND secure. [Kim+16] is fh-IND secure in the generic group model.
   - One can sample a random ciphertext $\mathbf{c_v}$, but then it is difficult to find any $\mathbf{c_x}$ such that $\mathsf{FE.Dec}(\mathsf{pp}, \mathbf{c_x}, \mathbf{c_v}) \neq \perp$.
   - [DDM15; Kim+16] are $\mathcal{O}'_{\mathsf{KeyGen}}$-RUF secure by Theorem 10.

   (b) In [Lee+18; Che+21]:
   - The field size $|\mathbb{F}| = |\mathbb{Z}_q| = q$ is polynomial of λ
   - They prove security in a game that only allows the adversary to call $\mathcal{O}_{\mathsf{KeyGen}}$ once, and it must be before $\mathcal{O}_{\mathsf{Enc}}$.
   - They are not fh-IND secure.
   - They are also not RUF secure because one can sample random ciphertext $\mathbf{c_v}$.

3. In general, I think RUF security cannot be easliy proven without adding a signature.

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