

# Biometrics Authentication: Formalization and Instantiation

Keng-Yu Chen

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This report formalizes the biometric authentication scheme, including its structure, usage, and security analysis with a security game model.

## 1 Preliminaries

In this report, we assume

- $\lambda$  is the security parameter.
- $[m]$  denotes the set of integers  $\{1, 2, \dots, m\}$ .
- $\mathbb{Z}_q$  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  $f(n) = \text{negl}$ , and we may also use  $\text{negl}$  to represent an arbitrary negligible function.
- $\text{poly}$  is the class of polynomial functions. We may also use  $\text{poly}$  to represent an arbitrary polynomial function.
- We write sampling a value  $r$  from a distribution  $\mathcal{D}$  as  $r \leftarrow^s \mathcal{D}$ . If  $S$  is a finite set, then  $r \leftarrow^s S$  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 three types of inner product functional encryption schemes: function hiding functional encryption, two-input functional encryption, and two-client functional encryption. We will instantiate our biometric authentication scheme using these primitives.

**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 FE.Setup, FE.KeyGen, FE.Enc, and FE.Dec:

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

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

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

Instantiation using an fh-IPFE scheme is given in Section 2.3.

**Definition 2** (Two-Input Inner Product Functional Encryption (adapted from [PP22])). A *two-input inner product functional encryption* (2i-IPFE) scheme FE for a field  $\mathbb{F}$  and input length  $k$  is composed of PPT algorithms FE.Setup, FE.KeyGen, FE.Enc, and FE.Dec:

- $\text{FE.Setup}(1^\lambda) \rightarrow \text{sk}, \text{ek}_1, \text{ek}_2$ : It outputs a secret key  $\text{sk}$  and two encryption keys  $\text{ek}_1, \text{ek}_2$ .
- $\text{FE.KeyGen}(\text{sk}, \mathbf{A}) \rightarrow \text{dk}_{\mathbf{A}}$ : It generates the functional decryption key  $\text{dk}_{\mathbf{A}}$  for a diagonal matrix  $\mathbf{A} \in \mathbb{F}^{k \times k}$ ,
- $\text{FE.Enc}(\text{ek}_i, \mathbf{x}) \rightarrow \mathbf{c}_{\mathbf{x}}$ : Given an encryption key, either  $\text{ek}_1$  or  $\text{ek}_2$ , it encrypts the input vector  $\mathbf{x} \in \mathbb{F}^k$  to the ciphertext  $\mathbf{c}_{\mathbf{x}}$ .
- $\text{FE.Dec}(\text{dk}_{\mathbf{A}}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow z$ : It outputs a value  $z \in \mathbb{F}$ .

Correctness: The 2i-IPFE scheme FE is *correct* if  $\forall (\text{sk}, \text{ek}_1, \text{ek}_2) \leftarrow \text{FE.Setup}(1^\lambda)$ ,  $\mathbf{A} \in \mathbb{F}^{k \times k}$ , and  $\mathbf{x}, \mathbf{y} \in \mathbb{F}^k$ , we have

$$\text{FE.Dec}(\text{FE.KeyGen}(\text{sk}, \mathbf{A}), \text{FE.Enc}(\text{ek}_1, \mathbf{x}), \text{FE.Enc}(\text{ek}_2, \mathbf{y})) = \mathbf{x}\mathbf{A}\mathbf{y}^T \in \mathbb{F}.$$

Instantiation using a 2i-IPFE is given in Section 2.4.

**Definition 3** (Two-Client Inner Product Functional Encryption (adapted from [PP22])). A *two-client inner product functional encryption* (2c-IPFE) scheme FE for a field  $\mathbb{F}$  and input length  $k$  is composed of PPT algorithms FE.Setup, FE.KeyGen, FE.Enc, and FE.Dec:

- $\text{FE.Setup}(1^\lambda) \rightarrow \text{sk}, \text{ek}_1, \text{ek}_2$ : It outputs a secret key  $\text{sk}$  and two encryption keys  $\text{ek}_1, \text{ek}_2$ .
- $\text{FE.KeyGen}(\text{sk}, \mathbf{A}) \rightarrow \text{dk}_{\mathbf{A}}$ : It generates the functional decryption key  $\text{dk}_{\mathbf{A}}$  for a diagonal matrix  $\mathbf{A} \in \mathbb{F}^{k \times k}$ ,

- $\text{FE.Enc}(\ell, \text{ek}_i, \mathbf{x}) \rightarrow \mathbf{c}_x$ : Given a label  $\ell$  and an encryption key, either  $\text{ek}_1$  or  $\text{ek}_2$ , it encrypts the input vector  $\mathbf{x} \in \mathbb{F}^k$  to the ciphertext  $\mathbf{c}_x$ .
- $\text{FE.Dec}(\text{dk}_A, \mathbf{c}_x, \mathbf{c}_y) \rightarrow z$ : It outputs a value  $z \in \mathbb{F}$ .

Correctness: The 2c-IPFE scheme FE is *correct* if  $\forall(\text{sk}, \text{ek}_1, \text{ek}_2) \leftarrow \text{FE.Setup}(1^\lambda), \mathbf{A} \in \mathbb{F}^{k \times k}$ , label  $\ell$ , and  $\mathbf{x}, \mathbf{y} \in \mathbb{F}^k$ , we have

$$\text{FE.Dec}(\text{FE.KeyGen}(\text{sk}, \mathbf{A}), \text{FE.Enc}(\ell, \text{ek}_1, \mathbf{x}), \text{FE.Enc}(\ell, \text{ek}_2, \mathbf{y})) = \mathbf{x} \mathbf{A} \mathbf{y}^T \in \mathbb{F}.$$

Instantiation using a 2c-IPFE is given in Section 2.5.

We also consider an instantiation using a relational hash scheme.

**Definition 4** (Relational Hash (adapted from [MR14])). Let  $R_\lambda$  be a relation over sets  $X_\lambda, Y_\lambda$ , and  $Z_\lambda$ . A *relational hash* scheme RH for  $R_\lambda$  consists of PPT algorithms  $\text{RH.KeyGen}$ ,  $\text{RH.HASH}_1$ ,  $\text{RH.HASH}_2$ , and  $\text{RH.Verify}$ :

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

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

$$\Pr \left[ \begin{cases} \text{pk} \leftarrow \text{RH.KeyGen}(1^\lambda) \\ \mathbf{h}_x \leftarrow \text{RH.Hash}_1(\text{pk}, \mathbf{x}) \\ \mathbf{h}_y \leftarrow \text{RH.Hash}_2(\text{pk}, \mathbf{y}) \end{cases} : \text{RH.Verify}(\text{pk}, \mathbf{h}_x, \mathbf{h}_y, \mathbf{z}) = R(\mathbf{x}, \mathbf{y}, \mathbf{z}) \right] = 1 - \text{negl}.$$

Instantiation using a relational hash is given in Section 2.6.

## 2 Formalization

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

- $\text{Setup}(1^\lambda) \rightarrow \text{esk}, \text{psk}, \text{csk}$ : It outputs the enrollment secret key  $\text{esk}$ , probe secret key  $\text{psk}$ , and compare secret key  $\text{csk}$ .
- $\text{encodeEnroll}^{\mathcal{O}_B}() \rightarrow \mathbf{x}$ : Given an oracle  $\mathcal{O}_B$ , which samples biometric data from the distribution  $\mathcal{B} \in \mathbb{B}$ , it encodes biometric samples as  $\mathbf{x}$ , the input format for enrollment.
- $\text{Enroll}(\text{esk}, \mathbf{x}) \rightarrow \mathbf{c}_x$ : It outputs the enrollment message  $\mathbf{c}_x$  from  $\mathbf{x}$ .

- $\text{encodeProbe}^{\mathcal{O}_{\mathcal{B}}}() \rightarrow \mathbf{y}$ : Given an oracle  $\mathcal{O}_{\mathcal{B}}$ , which samples biometric data from the distribution  $\mathcal{B} \in \mathbb{B}$ , it encodes biometric samples as  $\mathbf{y}$ , the input format for probe.
- $\text{Probe}(\text{psk}, \mathbf{y}) \rightarrow \mathbf{c}_{\mathbf{y}}$ : It outputs the probe message  $\mathbf{c}_{\mathbf{y}}$  from  $\mathbf{y}$ .
- $\text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow s$ : It compares the enrollment message  $\mathbf{c}_{\mathbf{x}}$  and probe message  $\mathbf{c}_{\mathbf{y}}$  and outputs a score  $s$ .
- $\text{Verify}(s) \rightarrow r \in \{0, 1\}$ : 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 discuss two usage models that employs the authentication scheme  $\Pi$ .

## 2.1 Usage Model – Device-of-User

In the model described in Figure 1 (an overview), Figure 2 (on enrollment), and Figure 3 (on authentication), users authenticate themselves to a server through their own devices and biometric scanners that are shared among different users. A key distribution service distributes keys for them. In practice, this model applies to the situation when the users access an online service run by the server.

- **User**: The user who enrolls its biometric data and authenticates itself to the server. We assume the user's biometric distribution is  $\mathcal{B} \in \mathbb{B}$ .
- **Scanner**: A machine to extract the user's biometric data by querying the oracle  $\mathcal{O}_{\mathcal{B}}$ .
- **Device**: A device belonging to the user. In practice, it can be a desktop or a mobile phone. It processes the **Enroll** and **Probe** functions for **User** with keys  $\text{esk}$  and  $\text{psk}$ . It queries  $\mathcal{O}_{\mathcal{B}}$  for biometric data through the **Scanner**.
- **KDS**: A key distribution service. It runs **Setup** to generate keys and distribute them to **Device** and **Server**.
- **Server**: The server responsible for authenticating the user. It stores the comparison key  $\text{csk}$  and the user's enrollment message  $\mathbf{c}_{\mathbf{x}}$ . On authentication, it compares the probe message with the registered enrollment message and returns the result.

The Device-of-User model, when instantiated by an fh-IPFE scheme (Section 2.3), is analogous to the use case presented in [EM23]. In their model, a user possesses a personal device, such as a smartphone or laptop, and a secure hardware device that runs an initial setup and stores all the keys, which corresponds to our KDS. On enrollment and authentication, the user inputs biometric templates onto the device, which corresponds to our **Scanner**. Subsequently, the device transmits the template to the secure hardware for the enrollment or probing processes, which are equivalent to our **Device**. In addition, they incorporate a two-factor authentication mechanism. The secure hardware also executes a digital signature scheme and sign the probe message on authentication.

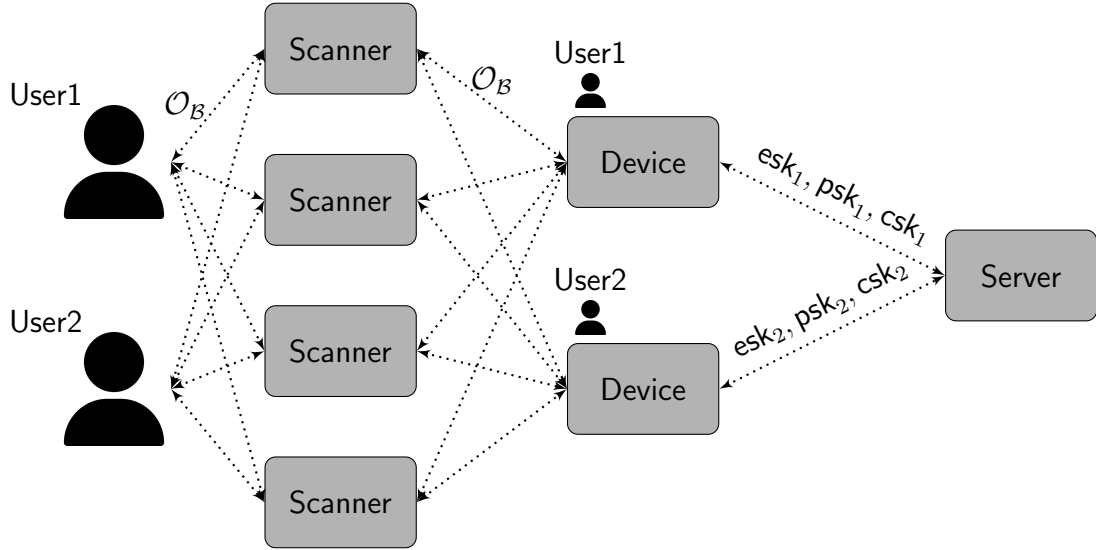


Figure 1: An Overview of the Device-of-User Usage Model

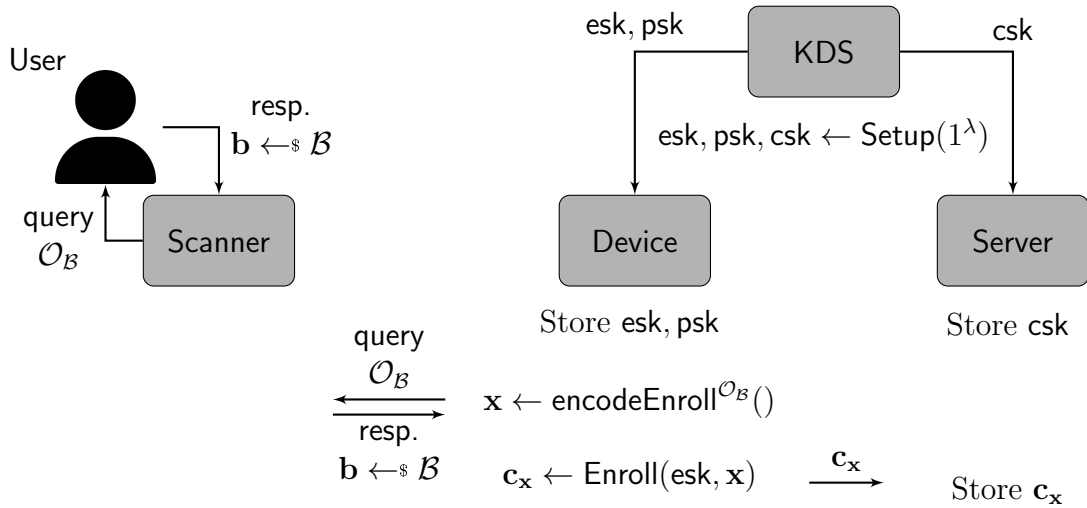


Figure 2: Device-of-User Usage Model on Enrollment

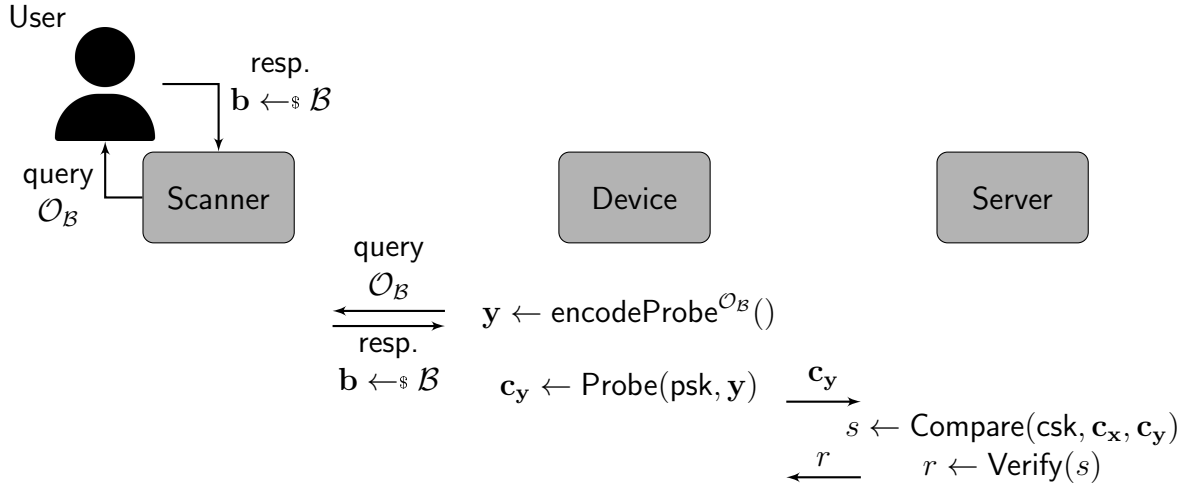


Figure 3: Device-of-User Usage Model on Authentication

## 2.2 Usage Model – Device-of-Domain

In the model described in Figure 4 (an overview), Figure 5 (on enrollment), and Figure 6 (on authentication), users first enroll themselves at an enrollment station and then authenticate themselves to a server through devices that belong to a domain. A key distribution service distributes enrollment keys to the enrollment station, probe keys to the domain, and comparison keys to the server. In practice, a domain can be a department in an organization, and this model applies to the situation when a user wants to access a public service of a department, such as a restricted area or instruments.

- **User**: The user who enrolls its biometric data at an enrollment station and authenticates itself to the server. We assume the user's biometric distribution is  $\mathcal{B} \in \mathbb{B}$ .
- **Domain**: A domain that owns several devices, all of which share one enrollment key  $\text{esk}$ , one probe key  $\text{psk}$  and one comparison key  $\text{csk}$ . Only the probe key is stored at each device of a domain. The enrollment key is stored at the enrollment station, and the comparison key is stored at the server. In practice, a domain can be a department, and users enroll and authenticate themselves before accessing a restricted service of this department.
- **Scanner**: A machine to extract the user's biometric data by querying the oracle  $\mathcal{O}_B$ .
- **Station**: An enrollment station responsible for collecting the user's biometric data to enroll them for a domain on the server.
- **Device**: A device belonging to a domain. In practice, it can be a device checking identities for a restricted area or an instrument. It owns a probe key  $\text{psk}$  and processes the  $\text{Probe}$  function for enrolled users of this domain.

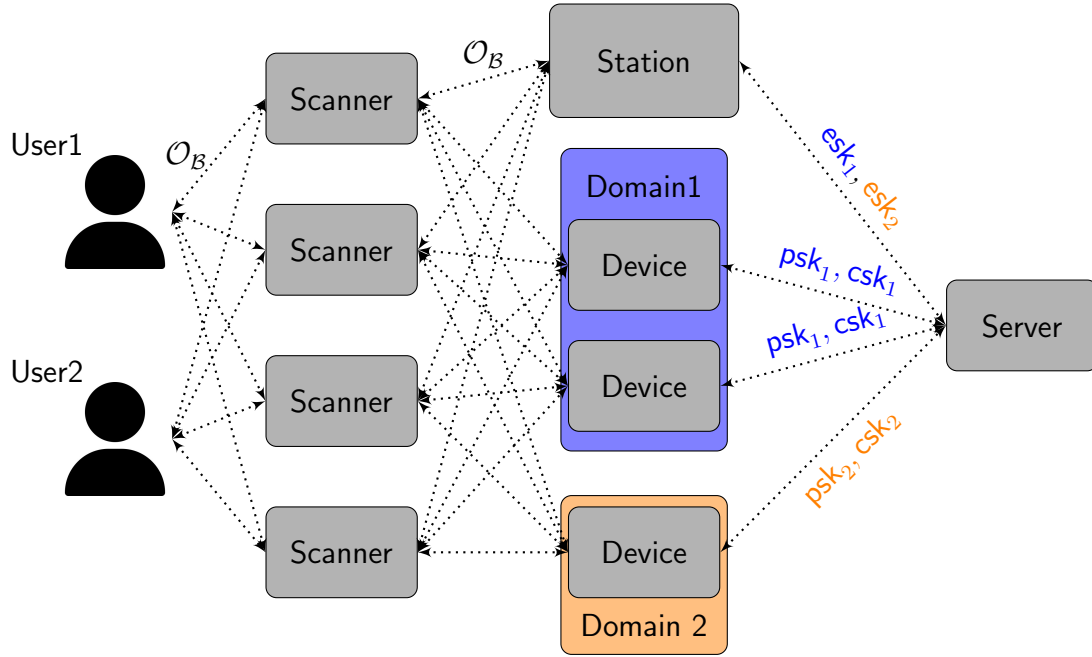


Figure 4: An overview of the Device-of-Domain Usage Model

- **KDS:** A key distribution service. It runs **Setup** to generate keys and distribute them to **Station**, **Domain**, and **Server**.
- **Server:** The server responsible for authenticating the user. It stores the comparison key  $csk$  for each domain and the user's enrollment message  $c_x$ . On authentication, it compares the probe message with the registered enrollment message and returns the result.

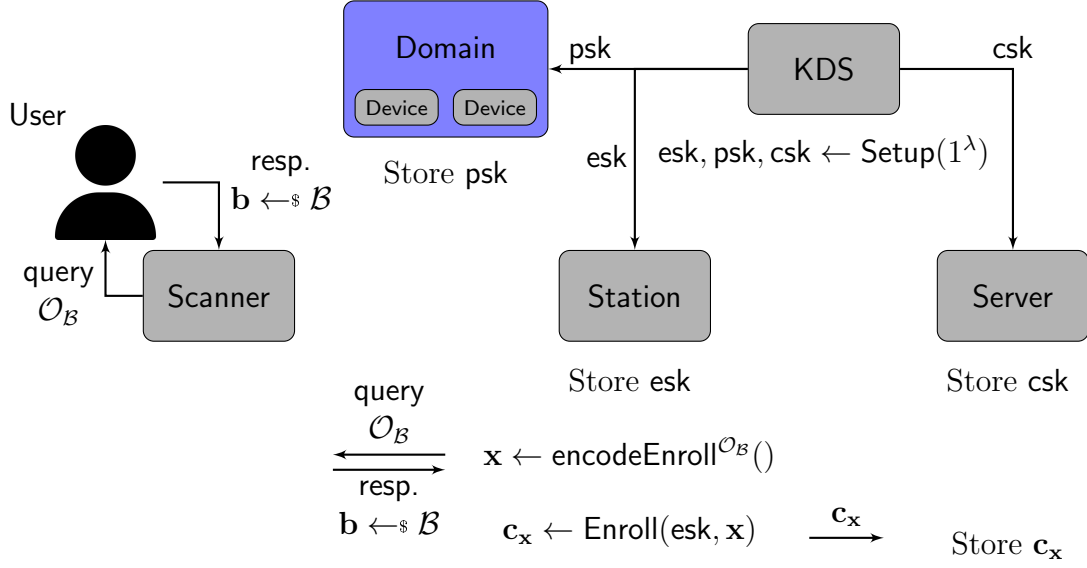


Figure 5: Device-of-Domain Usage Model on Enrollment

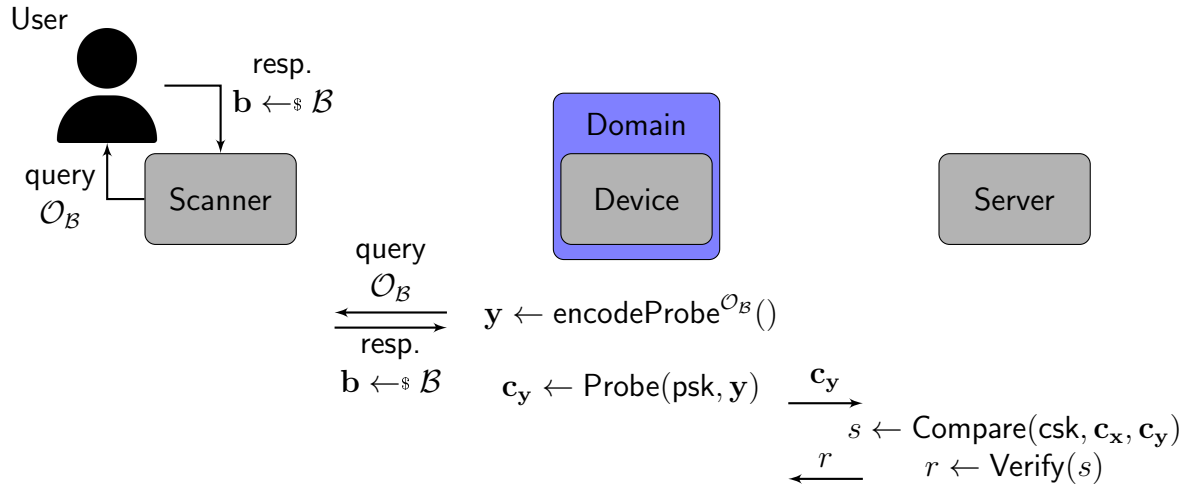


Figure 6: Device-of-Domain Usage Model on Authentication



### 2.3 Instantiation with an fh-IPFE Scheme

Let  $\text{FE} = (\text{FE.Setup}, \text{FE.KeyGen}, \text{FE.Enc}, \text{FE.Dec})$  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.

- **Setup( $1^\lambda$ )**: It calls  $\text{FE.Setup}(1^\lambda) \rightarrow \text{msk}, \text{pp}$  and outputs  $\text{esk} \leftarrow (\text{msk}, \text{pp})$ ,  $\text{psk} \leftarrow (\text{msk}, \text{pp})$  and  $\text{csk} \leftarrow \text{pp}$ .
- **encodeEnroll $^{\mathcal{O}_B}()$** : For a template vector  $\mathbf{b} = (b_1, b_2, \dots, b_k)$  sampled from  $\mathcal{O}_B$ , the function encodes it as  $\mathbf{x} = (x_1, x_2, \dots, x_{k+2}) = (b_1, b_2, \dots, b_k, 1, \|\mathbf{b}\|^2)$ .
- **Enroll( $\text{esk}, \mathbf{x}$ )**: It calls  $\text{FE.KeyGen}(\text{msk}, \text{pp}, \mathbf{x}) \rightarrow f_{\mathbf{x}}$  and outputs  $\mathbf{c}_{\mathbf{x}} \leftarrow f_{\mathbf{x}}$ .
- **encodeProbe $^{\mathcal{O}_B}()$** : For a template vector  $\mathbf{b}' = (b'_1, b'_2, \dots, b'_k)$  sampled from  $\mathcal{O}_B$ , the function encodes it as  $\mathbf{y} = (y_1, y_2, \dots, y_{k+2}) = (-2b'_1, -2b'_2, \dots, -2b'_k, \|\mathbf{b}'\|^2, 1)$ .
- **Probe( $\text{psk}, \mathbf{y}$ )**: It calls  $\text{FE.Enc}(\text{msk}, \text{pp}, \mathbf{y}) \rightarrow \mathbf{c}_{\mathbf{y}}$  and outputs  $\mathbf{c}_{\mathbf{y}}$ .
- **Compare( $\text{csk}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}$ )**: It calls  $\text{FE.Dec}(\text{pp}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow s$  and outputs the value  $s$ .
- **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  $r = 0$ .

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

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

which is the square of the Euclidean distance between two templates  $\mathbf{b}$  and  $\mathbf{b}'$ . 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  $\text{csk}$  is public, and the enrollment secret key  $\text{esk}$  and probe secret key  $\text{psk}$  are the same. Anyone with access to the enrollment message  $\mathbf{c}_{\mathbf{x}}$  and either one of  $\text{esk}$ ,  $\text{psk}$ , or a probe oracle  $\text{Probe}(\text{psk}, \cdot)$  can probe some  $\mathbf{y}' \in \mathbb{Z}_q^{k+2}$  and find  $\mathbf{x}\mathbf{y}'^T$  to get partial or full information about  $\mathbf{x}$ . Even if the adversary can only sample random ciphertexts  $\mathbf{c}_{\mathbf{y}}$  without knowing  $\mathbf{y}$ , if the field size  $q$  is not large enough, one can find a forged  $\mathbf{c}_{\mathbf{y}^*}$  such that  $\mathbf{x}\mathbf{y}^{*T} \leq \tau$  to impersonate the user by sampling many times offline.

Therefore, **Server** must store  $\mathbf{c}_{\mathbf{x}}$  securely, to avoid such an attack from an adversary who can access the probe oracle; **Device** must protect its probe function, to avoid such an attack from a malicious **Server**.

In the Device-of-Domain model, we assume the probe oracle is public, just as everyone can try accessing a public service. A malicious **Station** or **Server**, who has the enrollment message  $\mathbf{c}_{\mathbf{x}}$ , can utilize this attack to retrieve information about **User**.

## 2.4 Instantiation with a 2i-IPFE Scheme

Let  $\text{FE} = (\text{FE.Setup}, \text{FE.KeyGen}, \text{FE.Enc}, \text{FE.Dec})$  be a 2i-IPFE scheme we defined in Definition 2. Following the scheme in Section 2.3, we can instantiate a biometric authentication scheme using FE.

- $\text{Setup}(1^\lambda)$ : It calls  $\text{FE.Setup}(1^\lambda) \rightarrow \text{sk}, \text{ek}_1, \text{ek}_2$ ,  $\text{FE.KeyGen}(\text{sk}, \mathbf{I}_{k+2}) \rightarrow \text{dk}_{\mathbf{I}}$ , where  $\mathbf{I}_{k+2}$  is an identity matrix of size  $(k+2) \times (k+2)$ . It outputs  $\text{esk} \leftarrow \text{ek}_1$ ,  $\text{psk} \leftarrow \text{ek}_2$ , and  $\text{csk} \leftarrow \text{dk}_{\mathbf{I}}$
- $\text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}(), \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}}}()$ : The same as the scheme in 2.3.
- $\text{Enroll}(\text{esk}, \mathbf{x})$ : It calls  $\text{FE.Enc}(\text{ek}_1, \mathbf{x}) \rightarrow \mathbf{c}_{\mathbf{x}}$  and outputs  $\mathbf{c}_{\mathbf{x}}$ .
- $\text{Probe}(\text{psk}, \mathbf{y})$ : It calls  $\text{FE.Enc}(\text{ek}_2, \mathbf{y}) \rightarrow \mathbf{c}_{\mathbf{y}}$  and outputs  $\mathbf{c}_{\mathbf{y}}$ .
- $\text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}})$ : It calls  $\text{FE.Dec}(\text{dk}_{\mathbf{I}}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow s$  and outputs the value  $s$ .
- $\text{Verify}(s)$ : If  $\sqrt{s} \leq \tau$ , a pre-defined threshold for comparing the closeness of two templates, then it outputs  $r = 1$ ; otherwise, it outputs  $r = 0$ .

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

$$s = \text{FE.Dec}(\text{dk}_{\mathbf{I}}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) = \mathbf{x}\mathbf{I}_{k+2}\mathbf{y}^T = \mathbf{x}\mathbf{y}^T = \|\mathbf{b} - \mathbf{b}'\|^2.$$

just as the scheme in Section 2.3

Unlike the previous scheme, instantiated with a 2i-IPFE scheme in this way, the comparison secret key  $\text{csk}$  is now secret, and the enrollment secret key  $\text{esk}$  and probe secret key  $\text{psk}$  are distinct. Without  $\text{csk}$ , one cannot compare an enrollment message  $\mathbf{c}_{\mathbf{x}}$  and a probe message  $\mathbf{c}_{\mathbf{y}}$ . We can also transmit  $\mathbf{c}_{\mathbf{x}}$  in a public channel and store it in a public storage, under necessary security requirements of the 2i-IPFE scheme, such as indistinguishability of  $\mathbf{c}_{\mathbf{x}}$ .

In the Device-of-Domain model, the indistinguishability of  $\mathbf{c}_{\mathbf{x}}$  is against an adversary who has a probe oracle  $\text{Probe}(\text{psk}, \cdot)$ . If **Server** is malicious, then it can use  $\text{csk}$  to distinguish  $\mathbf{c}_{\mathbf{x}}$  enrolled by different samples. Therefore, we must limit the adversary's ability. For example, we can require the adversary to distinguish biometric vectors sampled from distributions in a pre-defined pool, and the adversary can only probe vectors randomly sampled from a distribution in the pool. We can also limit the rate of the probe oracle.

## 2.5 Instantiation with a 2c-IPFE Scheme

Note that if labels remain constant, a 2c-IPFE scheme is reduced to a 2i-IPFE scheme. Therefore, we can consider utilizing the label to represent each domain in the Device-of-Domain model. Let  $\text{FE} = (\text{FE.Setup}, \text{FE.KeyGen}, \text{FE.Enc}, \text{FE.Dec})$  be a 2c-IPFE scheme we defined in Definition 3. Following the scheme in Section 2.4, we can instantiate a biometric authentication scheme using FE.

- **Setup**( $1^\lambda$ ): It calls  $\text{FE.Setup}(1^\lambda) \rightarrow \text{sk}, \text{ek}_1, \text{ek}_2$ ,  $\text{FE.KeyGen}(\text{sk}, \mathbf{I}_{k+2}) \rightarrow \text{dk}_{\mathbf{I}}$ , where  $\mathbf{I}_{k+2}$  is an identity matrix of size  $(k+2) \times (k+2)$ . For keys used for Domain  $\ell$ , it outputs  $\text{esk} \leftarrow (\ell, \text{ek}_1)$ ,  $\text{psk} \leftarrow (\ell, \text{ek}_2)$ , and  $\text{csk} \leftarrow \text{dk}_{\mathbf{I}}$ .

Note that when the previous 2i-IPFE-based scheme in Section 2.4 is applied to a Device-of-Domain model, we assume that **Setup** is run once for each domain to generate different  $\text{esk}$ ,  $\text{psk}$ ,  $\text{csk}$ . In the scheme in this section, however, **Setup** is run only once for all the domains, and each domain shares the same  $\text{csk}$  and the same  $\text{esk}$ ,  $\text{psk}$  except different labels.

- $\text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ ,  $\text{encodeProbe}^{\mathcal{O}_{\mathcal{B}}}()$ : The same as the scheme in 2.4.
- **Enroll**( $\text{esk}, \mathbf{x}$ ): It calls  $\text{FE.Enc}(\ell, \text{ek}_1, \mathbf{x}) \rightarrow \mathbf{c}_{\mathbf{x}}$  and outputs  $\mathbf{c}_{\mathbf{x}}$ .
- **Probe**( $\text{psk}, \mathbf{y}$ ): It calls  $\text{FE.Enc}(\ell, \text{ek}_2, \mathbf{y}) \rightarrow \mathbf{c}_{\mathbf{y}}$  and outputs  $\mathbf{c}_{\mathbf{y}}$ .
- **Compare**( $\text{csk}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}$ ): It calls  $\text{FE.Dec}(\text{dk}_{\mathbf{I}}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) \rightarrow s$  and outputs the value  $s$ .
- **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  $r = 0$ .

By the correctness of the functional encryption scheme FE, if the labels of  $\mathbf{c}_{\mathbf{x}}$  and  $\mathbf{c}_{\mathbf{y}}$  are the same (they are of the same domain), we have

$$s = \text{FE.Dec}(\text{dk}_{\mathbf{I}}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}) = \mathbf{x} \mathbf{I}_{k+2} \mathbf{y}^T = \|\mathbf{b} - \mathbf{b}'\|^2.$$

just as the scheme in Section 2.4

When the Device-of-Domain model is instantiated with a 2c-IPFE scheme in this way, the enrollment secret key  $\text{esk}$  and probe secret key  $\text{psk}$  are now shared among all the devices, regardless of their domains. Therefore, to let a malicious or broken Domain not threaten other honest ones, one needs to make sure given  $\text{esk}$  or  $\text{psk}$ ,  $\mathbf{c}_{\mathbf{x}}$  still does not leak information about  $\mathbf{x}$ . This is different from the scheme in Section 2.4, where we only need security against an adversary who has a probe oracle  $\text{Probe}(\text{psk}, \cdot)$ .

If Server and Domain are both malicious, then the adversary can use  $\text{csk}$  to distinguish  $\mathbf{c}_{\mathbf{x}}$  and even recover  $\mathbf{x}$ . Therefore, we assume at most one party of them can be malicious at the same time. Note that this is the same as the 2i-IPFE-based scheme, where only one of Server and Domain can be malicious.

## 2.6 Instantiation with a Relational Hash Scheme

Let  $\text{RH} = (\text{RH.KeyGen}, \text{RH.Hash}_1, \text{RH.Hash}_2, \text{RH.Verify})$  be a relational hash scheme we defined in Definition 4 for the relation  $R$  of Hamming distance proximity parametrized by a constant  $\tau$ .

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

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

- $\text{Setup}(1^\lambda)$ : It calls  $\text{RH.Setup}(1^\lambda) \rightarrow \text{pk}$  and outputs  $\text{esk} \leftarrow \text{pk}$ ,  $\text{psk} \leftarrow \text{pk}$ , and  $\text{csk} \leftarrow \text{pk}$ .
- $\text{encodeEnroll}^{\mathcal{O}_B}()$ : For a template vector  $\mathbf{b}$  sampled from  $\mathcal{O}_B$ , it directly outputs  $\mathbf{x} \leftarrow \mathbf{b}$ .
- $\text{Enroll}(\text{esk}, \mathbf{x})$ : It calls  $\text{RH.Hash}_1(\text{pk}, \mathbf{x}) \rightarrow \mathbf{h}_x$  and outputs  $\mathbf{c}_x \leftarrow \mathbf{h}_x$ .
- $\text{encodeProbe}^{\mathcal{O}_B}()$ : For a template vector  $\mathbf{b}'$  sampled from  $\mathcal{O}_B$ , it directly outputs  $\mathbf{y} \leftarrow \mathbf{b}'$ .
- $\text{Probe}(\text{psk}, \mathbf{y})$ : It calls  $\text{RH.Hash}_2(\text{pk}, \mathbf{y}) \rightarrow \mathbf{h}_y$  and outputs  $\mathbf{c}_y \leftarrow \mathbf{h}_y$ .
- $\text{Compare}(\text{csk}, \mathbf{c}_x, \mathbf{c}_y)$ : It calls  $\text{RH.Verify}(\text{pk}, \mathbf{h}_x, \mathbf{h}_y) \rightarrow s$  and outputs the value  $s$ .
- $\text{Verify}(s)$ : It directly returns  $r \leftarrow s$ .

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

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

### 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 has an excessively large size for a PPT adversary to enumerate. We then provide interfaces for all algorithms to interact with  $\mathbb{B}$ .

- $\text{BioSamp}()$ : 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  $\mathcal{B} \leftarrow \text{BioSamp}()$  as  $\mathcal{B} \leftarrow_{\$} \mathbb{B}$ .
- $\text{BioDelete}(\mathcal{B})$ : Delete  $\mathcal{B}$  from  $\mathbb{B}$ . Consequently, no further access to  $\text{BioSamp}$  can derive  $\mathcal{B}$ . For simplicity, we write  $\text{BioDelete}(\mathcal{B})$  as  $\mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ .
- $\text{TempSamp}(\mathcal{B})$ : Let  $\mathcal{B}$  be a biometric distribution in  $\mathbb{B}$ . This algorithm samples a biometric template from  $\mathcal{B}$ . For simplicity, we write  $\mathbf{b} \leftarrow \text{TempSamp}(\mathcal{B})$  as  $\mathbf{b} \leftarrow_{\$} \mathcal{B}$ .
- $\mathcal{O}_{\text{samp}}(\cdot)$ : On input an index  $i$ ,
  - If  $i$  was not queried before, it first samples a biometric distribution  $\mathcal{B}_i \in \mathbb{B}$  by  $\text{BioSamp}$  and then outputs a biometric template sampled from the distribution  $\mathcal{B}_i$ , denoted by  $\mathbf{b} \leftarrow_{\$} \mathcal{B}_i$ .
  - If  $i$  has been queried before, it outputs a biometric template sampled from the distribution  $\mathcal{B}_i$ , denoted by  $\mathbf{b} \leftarrow_{\$} \mathcal{B}_i$ .

### 3.1 Unforgeability

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

---

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


---

```

1:  $\mathcal{B} \leftarrow \mathbb{B}, \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ 
2:  $\text{esk}, \text{psk}, \text{csk} \leftarrow \text{Setup}(1^\lambda)$ 
3:  $\mathbf{x} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ 
4:  $\mathbf{c}_{\mathbf{x}} \leftarrow \text{Enroll}(\text{esk}, \mathbf{x})$ 
5:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}(\text{option})$ 
6:  $s \leftarrow \text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \tilde{\mathbf{z}})$ 
7: return  $\text{Verify}(s)$ 

```

---

The auxiliary information **option** can be nothing or include  $\mathbf{c}_{\mathbf{x}}, \text{esk}, \text{psk}, \text{csk}$  or the following oracles:

- $\mathcal{O}_{\mathcal{B}}$ : It outputs a biometric sample  $\mathbf{b} \leftarrow \mathcal{B}$ .
- $\mathcal{O}_{\text{Enroll}}(\text{esk}, \cdot)$ : On input  $\mathbf{x}'$ , it outputs the enrollment message  $\text{Enroll}(\text{esk}, \mathbf{x}')$ .
- $\mathcal{O}_{\text{Probe}}(\text{psk}, \cdot)$ : On input  $\mathbf{y}'$ , it outputs the probe message  $\text{Probe}(\text{psk}, \mathbf{y}')$ . If this oracle and  $\mathcal{O}_{\mathcal{B}}$  are given at the same time, we require the adversary to return some  $\tilde{\mathbf{z}}$  that is not equal to any previous answer of  $\mathcal{O}_{\text{Probe}}$ .
- $\mathcal{O}_{\log}^q(\text{csk}, \mathbf{c}_{\mathbf{x}}, \cdot)$ : This is a resource-limited oracle. If it has been queried over  $q$  times in total, it aborts. Otherwise, on input  $\mathbf{z}$ , it first computes  $\mathbf{c}_{\mathbf{z}} \leftarrow \text{Probe}(\text{psk}, \mathbf{z})$  and outputs  $\text{Verify}(\text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{z}}))$ . We omit  $q$  in the superscript when we allow unbounded number of queries.
- $\mathcal{O}_{\text{auth}}^q(\text{csk}, \cdot, \cdot)$ : This is a resource-limited oracle. If it has been queried over  $q$  times in total, it aborts. Otherwise, on input  $\tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}$ , it outputs  $\text{Verify}(\text{Compare}(\text{csk}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}))$ . We omit  $q$  in the superscript when we allow unbounded number of queries.
- $\mathcal{O}'_{\text{Enroll}}(\cdot)$ : On input  $\text{esk}'$ , it first samples  $\mathbf{x}' \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$  and outputs  $\text{Enroll}(\text{esk}', \mathbf{x}')$ .
- $\mathcal{O}'_{\text{Probe}}(\cdot)$ : On input  $\text{psk}'$ , it first samples  $\mathbf{y}' \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}}}()$  and outputs  $\text{Probe}(\text{psk}', \mathbf{y}')$ . This oracle and  $\text{psk}$  should not be given at the same time.

If **option** does not include  $\text{psk}$  or  $\mathcal{O}_{\text{Probe}}$ , we define the advantage of an adversary  $\mathcal{A}$  with **option** in the UF game of a scheme  $\Pi$  associated with a family of distributions  $\mathbb{B}$  as

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

When **option** includes **psk** or  $\mathcal{O}_{\text{Probe}}$ , to consider potential non-negligible false positive rates of biometrics match, we define the plain  $\text{UF}'$  game in Algorithm 2, where the adversary has only  $\mathcal{O}_{\text{samp}}$  and  $\mathcal{O}_{\text{log}}^q$  and tries to find a vector  $\tilde{\mathbf{z}}$  close to  $\mathbf{x}$ .

---

**Algorithm 2**  $\text{UF}'_{\Pi, \mathbb{B}}(\mathcal{A}')$ 


---

```

1:  $\mathcal{B} \leftarrow \mathbb{B}, \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ 
2:  $\text{esk}, \text{psk}, \text{csk} \leftarrow \text{Setup}(1^\lambda)$ 
3:  $\mathbf{x} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ 
4:  $\mathbf{c}_{\mathbf{x}} \leftarrow \text{Enroll}(\text{esk}, \mathbf{x})$ 
5:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}'^{\mathcal{O}_{\text{log}}^q}()$ 
6:  $\tilde{\mathbf{c}}_{\tilde{\mathbf{z}}} \leftarrow \text{Probe}(\text{psk}, \tilde{\mathbf{z}})$ 
7:  $s \leftarrow \text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\tilde{\mathbf{z}}})$ 
8: return  $\text{Verify}(s)$ 

```

---

The advantage of an adversary  $\mathcal{A}$  is defined as

$$\text{Adv}_{\Pi, \mathbb{B}, \mathcal{A}, \text{option}}^{\text{UF}} := \max\{\Pr[\text{UF}_{\Pi, \mathbb{B}, \text{option}}(\mathcal{A}) \rightarrow 1] - \sup_{\text{PPT } \mathcal{A}'} \Pr[\text{UF}'_{\Pi, \mathbb{B}}(\mathcal{A}') \rightarrow 1], 0\}.$$

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

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

For the rest of this report, if the scheme, the family distribution, and the auxiliary information **option** are clear from context, we omit the subscript and write the game as  $\text{UF}(\mathcal{A})$ . 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  $\text{UF}_{\Pi, \mathbb{B}, \text{option}}$  game and rule out trivial attacks. We use the instantiation in Section 2.3 as an example to illustrate.

For a biometric distribution  $\mathcal{B} \in \mathbb{B}$  and  $\mathbf{b} \leftarrow \mathcal{B}$ , define the *true positive rates* TP.

$$\begin{aligned} \text{TP}(\mathcal{B}, \mathbf{b}) &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathbf{b}' \leftarrow \mathcal{B}] \\ \text{TP}(\mathcal{B}) &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathbf{b}, \mathbf{b}' \leftarrow \mathcal{B}] = \mathbb{E}_{\mathbf{b} \leftarrow \mathcal{B}}[\text{TP}(\mathcal{B}, \mathbf{b})] \\ \text{TP} &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathcal{B} \leftarrow \mathbb{B}, \mathbf{b}, \mathbf{b}' \leftarrow \mathcal{B}] = \mathbb{E}_{\mathcal{B} \leftarrow \mathbb{B}}[\text{TP}(\mathcal{B})] \end{aligned}$$

We also define *false positive rates* FP.

$$\begin{aligned} \text{FP}(\mathbf{b}) &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathcal{B}' \leftarrow \mathbb{B}, \mathbf{b}' \leftarrow \mathcal{B}'] \\ \text{FP}(\mathcal{B}) &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathbf{b} \leftarrow \mathcal{B}, \mathcal{B}' \leftarrow \mathbb{B}, \mathbf{b}' \leftarrow \mathcal{B}'] = \mathbb{E}_{\mathbf{b} \leftarrow \mathcal{B}}[\text{FP}(\mathbf{b})] \\ \text{FP} &:= \Pr[\|\mathbf{b} - \mathbf{b}'\| \leq \tau : \mathcal{B}, \mathcal{B}' \leftarrow \mathbb{B}, \mathbf{b} \leftarrow \mathcal{B}, \mathbf{b}' \leftarrow \mathcal{B}'] = \mathbb{E}_{\mathcal{B} \leftarrow \mathbb{B}}[\text{FP}(\mathcal{B})] \end{aligned}$$

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. The use of plain UF' game is to prevent an UF game adversary from leveraging a non-negligible FP. If option includes psk or  $\mathcal{O}_{\text{Probe}}$ , the UF adversary  $\mathcal{A}$  in Algorithm 3 can enjoy a winning rate of FP.

---

**Algorithm 3**  $\mathcal{A}(\text{psk})$  ( or  $\mathcal{A}^{\mathcal{O}_{\text{Probe}}}$  )
 

---

```

1:  $\mathcal{B}' \leftarrow_{\$} \mathbb{B}$ 
2:  $\mathbf{y} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}'}}()$ 
3:  $\mathbf{c}_{\mathbf{y}} \leftarrow \text{Probe}(\text{psk}, \mathbf{y})$        $\triangleright$  or  $\mathbf{c}_{\mathbf{y}} \leftarrow \mathcal{O}_{\text{Probe}}(\mathbf{y})$ 
4: return  $\mathbf{c}_{\mathbf{y}}$ 

```

---

We note that an UF' adversary can have the same winning probability by returning  $\mathbf{y} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}'}}()$ . Moreover, to capture the circumstance when everyone, including the adversary, can try to log in, we provide the oracle  $\mathcal{O}_{\log}^q$ , which can boost the winning probability of an UF' adversary to around  $q \cdot \text{FP}$  if  $\text{FP}(\mathbf{b})$  is small in general.

$$\mathbb{E}_{\mathcal{B} \leftarrow_{\$} \mathbb{B}, \mathbf{b} \leftarrow_{\$} \mathcal{B}}[1 - (1 - \text{FP}(\mathbf{b}))^q] \approx \mathbb{E}_{\mathcal{B} \leftarrow_{\$} \mathbb{B}, \mathbf{b} \leftarrow_{\$} \mathcal{B}}[q \cdot \text{FP}(\mathbf{b})] = q \cdot \text{FP}$$

The scheme is considered secure when no UF adversaries can acquire a non-negligible advantage over this baseline.

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

If option includes csk,  $\mathbf{c}_{\mathbf{x}}$ , and either psk or  $\mathcal{O}_{\text{Probe}}$  but no  $\mathcal{O}_{\mathcal{B}}$ , the scheme cannot achieve UF security when FP is not negligible. An adversary can run  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}$  for  $\mathcal{A}$  in Algorithm 3 and  $\text{Compare}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \tilde{\mathbf{z}})$  to check if the answer is valid. By repeating this procedure poly times, its winning probability can be boosted to around poly  $\cdot$  FP.

If option includes  $\mathcal{O}'_{\text{Enroll}}$  and either psk or  $\mathcal{O}_{\text{Probe}}$  but no  $\mathcal{O}_{\mathcal{B}}$ , the adversary in Algorithm 4 can win with a probability

$$\Pr[\|\mathbf{b}^{(0)} - \mathbf{b}'\| \leq \tau \mid \|\mathbf{b}^{(1)} - \mathbf{b}'\| \leq \tau]$$

where  $\mathbf{b}^{(0)}, \mathbf{b}^{(1)} \leftarrow_{\$} \mathcal{B}$  and  $\mathbf{b}' \leftarrow_{\$} \mathcal{B}'$ . This value is in general not negligible. The expected number of repetitions is  $\mathbb{E}_{\mathcal{B} \leftarrow_{\$} \mathbb{B}} \left[ \frac{1}{\text{FP}(\mathcal{B})} \right]$ . If  $\text{FP}(\mathcal{B})$  is non-negligible, the adversary can return the answer in expected polynomial time. A similar adversary also exists when option includes  $\mathcal{O}'_{\text{Probe}}$  and  $\mathcal{O}_{\text{Probe}}$  but no  $\mathcal{O}_{\mathcal{B}}$ .

### 3.3 Indistinguishable against Malicious Server (IND-MSV)

In the game of Indistinguishable against Malicious Server, we model the ability of a malicious Server who tries to identify the user. The adversary  $\mathcal{A}$  is given oracles to two biometric distributions  $\mathcal{B}^{(0)}, \mathcal{B}^{(1)}$ , the comparison key csk, an enrollment message

---

**Algorithm 4**  $\mathcal{A}^{\mathcal{O}'_{\text{Enroll}}}(\text{psk})$  (or  $\mathcal{A}^{\mathcal{O}'_{\text{Enroll}}, \mathcal{O}_{\text{Probe}}}$ )

---

```

1:  $\text{esk}', \text{psk}', \text{csk}' \leftarrow \text{Setup}(1^\lambda)$ 
2: repeat
3:    $\mathcal{B}' \leftarrow_{\$} \mathbb{B}$ 
4:    $\mathbf{y}' \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}'}}()$ 
5:    $\mathbf{c}_{\mathbf{y}'}' \leftarrow \text{Probe}(\text{psk}', \mathbf{y}')$ 
6:    $\mathbf{c}_{\mathbf{x}'}' \leftarrow \mathcal{O}'_{\text{Enroll}}(\text{esk}')$ 
7: until  $\text{Verify}(\text{Compare}(\text{csk}', \mathbf{c}_{\mathbf{x}'}', \mathbf{c}_{\mathbf{y}'}')) = 1$ 
8:  $\mathbf{c}_{\mathbf{y}} \leftarrow \text{Probe}(\text{psk}, \mathbf{y}')$   $\triangleright$  or  $\mathbf{c}_{\mathbf{y}} \leftarrow \mathcal{O}_{\text{Probe}}(\mathbf{y}')$ 
9: return  $\mathbf{c}_{\mathbf{y}}$ 

```

---



---

**Algorithm 5**  $\text{IND-MSV}_{\Pi, \mathbb{B}}(\mathcal{A})$ 


---

```

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:  $\text{esk}, \text{psk}, \text{csk} \leftarrow \text{Setup}(1^\lambda)$ 
5:  $\mathbf{x} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}^{(b)}}}()$ 
6:  $\mathbf{c}_{\mathbf{x}} \leftarrow \text{Enroll}(\text{esk}, \mathbf{x})$ 
7: for  $i = 1$  to  $t$  do
8:    $\mathbf{y}^{(i)} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}^{(b)}}}()$ 
9:    $\mathbf{c}_{\mathbf{y}}^{(i)} \leftarrow \text{Probe}(\text{psk}, \mathbf{y}^{(i)})$ 
10: end for
11:  $\tilde{b} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}^{(0)}}, \mathcal{O}_{\mathcal{B}^{(1)}}}(\text{csk}, \mathbf{c}_{\mathbf{x}}, \{\mathbf{c}_{\mathbf{y}}^{(i)}\}_{i=1}^t)$ 
12: return  $1_{\tilde{b}=b}$ 

```

---

$\mathbf{c}_{\mathbf{x}}$ , and a list of  $t$  probe messages  $\{\mathbf{c}_{\mathbf{y}}^{(i)}\}_{i=1}^t$ . It tries to guess from either  $\mathcal{B}^{(0)}$  or  $\mathcal{B}^{(1)}$  these messages are generated. The whole game is defined in Algorithm 5.

We define the advantage of an adversary  $\mathcal{A}$  in the IND-MSV game of a scheme  $\Pi$  associated with a family of distributions  $\mathbb{B}$  as

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

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

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

## 4 Security Analysis

Given an fh-IPFE scheme FE, we define the fh-IND game in algorithm 6.

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



**Algorithm 6** fh-IND<sub>FE</sub>( $\mathcal{A}$ )

---

```

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

```

---

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

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

**Definition 5** (Admissible Adversary). Let  $\mathcal{A}$  be an adversary in an fh-IND game, and let  $(\mathbf{x}_1^{(0)}, \mathbf{x}_1^{(1)}), \dots, (\mathbf{x}_{Q_K}^{(0)}, \mathbf{x}_{Q_K}^{(1)})$  be its queries to  $\mathcal{O}_{\text{KeyGen}}$  and  $(\mathbf{y}_1^{(0)}, \mathbf{y}_1^{(1)}), \dots, (\mathbf{y}_{Q_E}^{(0)}, \mathbf{y}_{Q_E}^{(1)})$  be its queries to  $\mathcal{O}_{\text{Enc}}$ . 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 6** (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 fh-IND game in Algorithm 6 is

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

We also define the RUF game in algorithm 7 for a real number  $\gamma$ .

**Algorithm 7** RUF<sub>FE</sub> <sup>$\gamma$</sup> ( $\mathcal{A}$ )

---

```

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

```

---

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

**Definition 7** (RUF Security). An fh-IPFE scheme FE is called RUF secure for a real number  $\gamma$  if for any adversary  $\mathcal{A}$ , the advantage of  $\mathcal{A}$  in the RUF game in Algorithm 7 is

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

We note that by adding a sEUF-CMA signature scheme  $\text{Sig} = (\text{KeyGen}, \text{Sign}, \text{Verify})$ , an fh-IPFE scheme can be upgraded to an RUF secure scheme. In a bit more detail,

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

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

## 4.1 fh-IND Security and UF Security

Let  $\Pi$  be the authentication scheme instantiated by an fh-IPFE scheme  $\text{FE}$  as in Section 2.3.

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

*Proof.* Given an adversary  $\mathcal{A}$  in the  $\text{UF}_{\text{option}}$  game, consider the reduction adversary  $\mathcal{R}$  in Algorithm 14 which plays the fh-IND game.  $\mathcal{R}$  runs  $\mathcal{A}$  and simulates each oracle in the following way.

- $\mathcal{O}_{\text{auth}}(\text{csk}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}})$ : This is simulated by calling  $\text{Verify}(\text{FE.Dec}(\text{pp}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}))$ .
- $\mathcal{O}_{\text{Enroll}}(\text{esk}, \mathbf{x}')$ : This is simulated by  $\mathcal{O}_{\text{KeyGen}}(\mathbf{x}', \mathbf{x}')$  given in the fh-IND game.

Note that since  $\mathcal{R}$  never calls  $\mathcal{O}_{\text{Enc}}$ , it is an admissible adversary.

---

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

---

```

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

---

If the challenge bit  $b = 0$ , then  $\mathcal{R}$  perfectly simulates a  $\text{UF}_{\text{option}}$  game for  $\mathcal{A}$ . Therefore, the probability that  $\text{Verify}(s) = 1$  in Line 7 is  $\Pr[\text{UF}_{\text{option}}(\mathcal{A}) \rightarrow 1]$ .

For the case when the challenge bit  $b = 1$ , consider an adversary  $\mathcal{A}'$  in Algorithm 9 in the RUF game.  $\mathcal{A}'$  runs Line 1 and 5 of  $\mathcal{R}$  and simulates each oracle in the following way.

- $\mathcal{O}_{\text{auth}}(\text{csk}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}})$ : This is simulated by calling  $\text{Verify}(\text{FE}.\text{Dec}(\text{pp}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}))$ .
- $\mathcal{O}_{\text{Enroll}}(\text{esk}, \mathbf{x}')$ : This is simulated by  $\mathcal{O}'_{\text{KeyGen}}(\mathbf{x}')$  given in the RUF game.

---

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

---

1:  $\mathcal{B} \leftarrow \mathbb{B}, \quad \mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$   
 2:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\text{auth}}, \mathcal{O}'_{\text{KeyGen}}}(\mathbf{c})$   
 3: **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  $\text{Verify}(s) = 1$ , which is equivalent to  $s \leq \tau^2$ , in Line 7 is  $\Pr[\text{RUF}_{\text{FE}}^{\tau^2}(\mathcal{A}) \rightarrow 1]$

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

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

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

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

□

For **option** that includes  $\mathcal{O}_{\text{Probe}}$ , 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  $\mathbf{y}$  such that  $\mathbf{r}\mathbf{y}^T = d$ .

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

*Proof.* Given an adversary  $\mathcal{A}$  in the  $\text{UF}_{\text{option}}$  game, we will show that

$$\Pr[\text{UF}_{\text{option}}(\mathcal{A}) \rightarrow 1] = \text{negl}.$$

Hence, we can ignore the false positive rate  $\sup_{\text{PPT } \mathcal{A}'} \Pr[\text{UF}'_{\Pi, \mathbb{B}}(\mathcal{A}') \rightarrow 1]$ .

Consider the reduction adversary  $\mathcal{R}$  in Algorithm 10 which plays the fh-IND game.  $\mathcal{R}$  runs  $\mathcal{A}$  and simulates each oracle in the following way.

- $\mathcal{O}_{\text{auth}}^q(\text{csk}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}})$ : This is simulated by calling  $\text{Verify}(\text{FE.Dec}(\text{pp}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}))$ .
- $\mathcal{O}_{\text{Probe}}(\text{psk}, \mathbf{y}')$ : It first computes  $d \leftarrow \mathbf{x}\mathbf{y}'^T$  and finds a vector  $\mathbf{y}''$  such that  $\mathbf{r}\mathbf{y}''^T = d$ . Next, it calls  $\mathcal{O}_{\text{Enc}}(\mathbf{y}', \mathbf{y}'')$ , 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  $\mathcal{O}_{\text{KeyGen}}$ , and for any query  $(\mathbf{y}', \mathbf{y}'')$  to  $\mathcal{O}_{\text{Enc}}$ , it satisfies  $\mathbf{x}\mathbf{y}'^T = \mathbf{r}\mathbf{y}''^T$ . Hence,  $\mathcal{R}$  is an admissible adversary.

---

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


---

```

1:  $\mathcal{B} \leftarrow \mathbb{B}$ ,  $\mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ 
2:  $\mathbf{x} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ 
3:  $\mathbf{r} \leftarrow \mathbb{F}^{k+2}$ 
4:  $\mathbf{c} \leftarrow \mathcal{O}_{\text{KeyGen}}(\mathbf{x}, \mathbf{r})$ 
5:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}}, \mathcal{O}_{\text{auth}}^q, \mathcal{O}_{\text{Probe}}}(\mathbf{c})$ 
6: if  $\tilde{\mathbf{z}}$  is equal to any output of  $\mathcal{O}_{\text{Probe}}$  then
    return  $\perp$ 
7: end if
8:  $s \leftarrow \text{FE.Dec}(\text{pp}, \mathbf{c}, \tilde{\mathbf{z}})$ 
9: if  $\text{Verify}(s) = 1$  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  $\mathcal{R}$  perfectly simulates a  $\text{UF}_{\text{option}}$  game for  $\mathcal{A}$ . Therefore, the probability that  $\text{Verify}(s) = 1$  in Line 9 is  $\Pr[\text{UF}_{\text{option}}(\mathcal{A}) \rightarrow 1]$ .

For the case when the challenge bit  $b = 1$ , consider an adversary  $\mathcal{A}'$  in Algorithm 11 in the RUF game.  $\mathcal{A}'$  runs  $\mathcal{A}$  and simulates each oracle in the following way.

- $\mathcal{O}_{\text{auth}}^q(\text{csk}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}})$ : This is simulated by calling  $\text{Verify}(\text{FE.Dec}(\text{pp}, \tilde{\mathbf{c}}_{\mathbf{x}}, \tilde{\mathbf{c}}_{\mathbf{y}}))$ .
- $\mathcal{O}_{\text{Probe}}(\text{psk}, \mathbf{y}')$ : It first computes  $d \leftarrow \mathbf{x}^{(*)}\mathbf{y}'^T$  and finds a vector  $\mathbf{y}''$  such that  $\mathbf{r}\mathbf{y}''^T = d$ . Next, it calls  $\mathcal{O}'_{\text{Enc}}(\mathbf{y}'')$ , 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.

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

Let  $\mathcal{A}'$  play a tweaked  $\text{RUF}_{\text{FE}}^{\tau^2}$  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  $\mathcal{O}'_{\text{Enc}}$  called by  $\mathcal{O}_{\text{Probe}}$  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 fh-IND game

---

**Algorithm 11**  $\mathcal{A}'^{\mathcal{O}'_{\text{KeyGen}}, \mathcal{O}'_{\text{Enc}}}(\text{pp}, \mathbf{c})$ 


---

```

1:  $\mathcal{B} \leftarrow \mathbb{B}$ ,  $\mathbb{B} \leftarrow \mathbb{B} \setminus \mathcal{B}$ 
2:  $\mathbf{x}^{(*)} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}}}()$ 
3: Sample  $k + 2$  linearly independent vectors  $\{\mathbf{e}^{(i)}\}_{i=1}^{k+2}$ .
4: for  $i = 1$  to  $k + 2$  do
5:    $\mathbf{c}^{(i)} \leftarrow \mathcal{O}'_{\text{Enc}}(\mathbf{e}^{(i)})$ .
6:    $d_i \leftarrow \text{FE.Dec}(\text{pp}, \mathbf{c}, \mathbf{c}^{(i)})$ .
7: end for
8: Find the vector  $\mathbf{r}$  by solving the linear system  $\{\mathbf{r}\mathbf{e}^{(i)T} = d_i\}_{i=1}^{k+2}$ .
9: if  $\mathbf{r} = \mathbf{0}$  then
10:   return  $\perp$ 
11: end if
12:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}_{\text{samp}}, \mathcal{O}_{\text{samp}}(i^*), \mathcal{O}_{\text{auth}}^q, \mathcal{O}_{\text{Probe}}}(\mathbf{c})$ 
13: return  $\tilde{\mathbf{z}}$ 

```

---

when the challenge bit  $b = 1$  and  $V$ , and the other one is a relation between  $\mathcal{A}'$  playing a regular  $\text{RUF}_{\text{FE}}^{\tau^2}$  game and the tweaked one.

$$\Pr[\text{Verify}(s) = 1 \mid b = 1 \wedge \mathbf{r} \neq \mathbf{0}] = \Pr[V = 1] \quad (1)$$

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

For Equation 1, consider that

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

For Equation 2, consider that

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

Note that each  $\mathbf{c}^{(i)} = \text{FE.Enc}(\text{msk}, \text{pp}, \mathbf{e}^{(i)})$  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

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

Combining both results from Equation 1 and 2, we derive

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

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

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

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

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

□

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

**Definition 8.** For any distribution  $\mathcal{B} \in \mathbb{B}$  and an integer  $t$ , define the distribution  $\mathcal{D}_{\mathcal{B}}(t)$  as

$$\mathcal{D}_{\mathcal{B}}(t) = (\|\mathbf{b} - \mathbf{b}^{(1)}\|, \|\mathbf{b} - \mathbf{b}^{(2)}\|, \dots, \|\mathbf{b} - \mathbf{b}^{(t)}\|)$$

where  $\mathbf{b}, \mathbf{b}^{(1)}, \dots, \mathbf{b}^{(t)} \leftarrow_{\$} \mathcal{B}$ .

**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 when  $\Pi$  is instantiated by an fh-IPFE scheme as in Section 2.3, computational 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

$$\left( \sqrt{\text{FE.Dec}(\text{pp}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}^{(1)})}, \dots, \sqrt{\text{FE.Dec}(\text{pp}, \mathbf{c}_{\mathbf{x}}, \mathbf{c}_{\mathbf{y}}^{(t)})} \right) = \mathcal{D}_{\mathcal{B}^{(b)}}(t)$$

where  $b$  is the challenge bit.

**Algorithm 12**  $\mathcal{R}^{\mathcal{O}_{\text{KeyGen}}, \mathcal{O}_{\text{Enc}}}(\text{pp})$ 


---

```

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:  $\mathbf{x}^{(0)} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}^{(0)}}}()$ 
4:  $\mathbf{x}^{(1)} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}^{(1)}}}()$ 
5:  $\mathbf{c}_{\mathbf{x}} \leftarrow \mathcal{O}_{\text{KeyGen}}(\mathbf{x}^{(0)}, \mathbf{x}^{(1)})$ 
6: for  $i = 1$  to  $t$  do
7:    $\mathbf{y}^{(0)} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}^{(0)}}}()$ 
8:   repeat
9:      $\mathbf{y}^{(1)} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}^{(1)}}}()$ 
10:    until  $\mathbf{x}^{(0)} \mathbf{y}^{(0)T} = \mathbf{x}^{(1)} \mathbf{y}^{(1)T}$ 
11:    $\mathbf{c}_{\mathbf{y}}^{(i)} \leftarrow \mathcal{O}_{\text{Enc}}(\mathbf{y}^{(0)}, \mathbf{y}^{(1)})$ 
12: end for
13:  $\tilde{b} \leftarrow \mathcal{A}^{\mathcal{O}_{\mathcal{B}^{(0)}}, \mathcal{O}_{\mathcal{B}^{(1)}}}(\text{pp}, \mathbf{c}_{\mathbf{x}}, \{\mathbf{c}_{\mathbf{y}}^{(i)}\}_{i=1}^t)$ 
14: return  $\tilde{b}$ 

```

---

**Theorem 3.** *For any distribution family  $\mathbb{B}$  satisfying Assumption 1 and having a true positive rate  $TP > \frac{1}{\text{poly}}$ , if FE is fh-IND secure, then  $\Pi$  is IND-MSV secure.*

*Proof.* Given an adversary  $\mathcal{A}$  in the IND-MSV game, consider the reduction adversary  $\mathcal{R}$  in Algorithm 12 which plays the fh-IND game by running  $\mathcal{A}$ .

Note that  $(\mathbf{x}^{(0)}, \mathbf{x}^{(1)})$  is the only query of  $\mathcal{R}$  to  $\mathcal{O}_{\text{KeyGen}}$ , and for any query  $(\mathbf{y}^{(0)}, \mathbf{y}^{(1)})$  to  $\mathcal{O}_{\text{Enc}}$ , 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 10 is satisfied is

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

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

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

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

Now, we show that  $\mathcal{R}$  perfectly simulate an IND-MSV game for  $\mathcal{A}$ . If the challenge bit  $b$  of the fh-IND game is 0,  $\mathbf{c}_{\mathbf{x}}$  and  $\mathbf{c}_{\mathbf{y}}^{(i)}$  for all  $i \in [t]$  are generated from  $\mathcal{B}^{(0)}$  and

have the same distributions as the inputs for an adversary in IND-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  $\mathbf{X}^{(0)}$  and  $\mathbf{X}^{(1)}$  be the distribution of  $\{\mathbf{x}^{(0)} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}^{(0)}}}\}$  and  $\{\mathbf{x}^{(1)} \leftarrow \text{encodeEnroll}^{\mathcal{O}_{\mathcal{B}^{(1)}}}\}$ , respectively. Let  $\{\mathbf{Y}_i^{(0)}\}_{i=1}^t$  and  $\{\mathbf{Y}_i^{(1)}\}_{i=1}^t$  be  $t$  identical and independent distributions of  $\{\mathbf{y}^{(0)} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}^{(0)}}}\}$  and  $\{\mathbf{y}^{(1)} \leftarrow \text{encodeProbe}^{\mathcal{O}_{\mathcal{B}^{(1)}}}\}$ , respectively. Let  $\mathbf{Y}'_i$  be the distribution of  $\mathbf{y}^{(1)}$  derived after the loop in Line 10 in the  $i$ -th iteration. For any  $\{d_i\}_{i=1}^t, d_i > 0$ ,

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

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

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

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

In conclusion,

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

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



## 5 Rough Ideas

Define the  $\text{RUF}^{\mathcal{O}}$  game in algorithm 13 for a real number  $\gamma$ .

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**Algorithm 13**  $\text{RUF}_{\text{FE}}^{\mathcal{O}, \gamma}(\mathcal{A})$ 


---

```

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

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

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

**Definition 9** (RUF Security). An fh-IPFE scheme FE is called  $\mathcal{O}$ -RUF secure for a real number  $\gamma$  if for any adversary  $\mathcal{A}$ , the advantage of  $\mathcal{A}$  in the RUF game in Algorithm 7 is

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

**Theorem 4** (Theorem 1). *Let  $\text{option} = \{\mathbf{c}_x, \mathcal{O}_B, \mathcal{O}_{\text{auth}}, \mathcal{O}_{\text{Enroll}}\}$ . For any distribution family  $\mathbb{B}$ , if FE is fh-IND secure and  $\mathcal{O}'_{\text{KeyGen}}$ -RUF secure for a  $\gamma \geq \tau^2$ , then  $\Pi$  is option-unforgeable.*

**Theorem 5** (Theorem 2). *Let  $\text{option} = \{\mathbf{c}_x, \mathcal{O}_B, \mathcal{O}_{\text{auth}}, \mathcal{O}_{\text{Probe}}\}$ . For any distribution family  $\mathbb{B}$ , if FE is fh-IND secure and  $\mathcal{O}'_{\text{Enc}}(\cdot)$ -RUF secure for a  $\gamma \geq \tau^2$ , then  $\Pi$  is option-unforgeable.*

**Assumption 2.** Let  $\mathbf{x} \in \mathbb{F}^k, \mathbf{c} \leftarrow \text{FE.KeyGen}(\text{msk}, \text{pp}, \mathbf{x})$ . Assume that  $\text{FE.Dec}(\text{pp}, \mathbf{c}, \mathbf{z})$  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  $\mathbf{v} \in \mathbb{F}^k, \mathbf{v} \neq \mathbf{0}$  such that for any  $\mathbf{x} \in \mathbb{F}^k$  and  $\mathbf{c} \leftarrow \text{FE.KeyGen}(\text{msk}, \text{pp}, \mathbf{x})$ ,  $\text{FE.Dec}(\text{pp}, \mathbf{c}, \mathbf{z}) = \mathbf{x}\mathbf{v}^T$ .
- For any  $\mathbf{x} \in \mathbb{F}^k$  and  $\mathbf{c} \leftarrow \text{FE.KeyGen}(\text{msk}, \text{pp}, \mathbf{x})$ ,  $\text{FE.Dec}(\text{pp}, \mathbf{c}, \mathbf{z}) \rightarrow \perp$ .

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

**Theorem 6.** *Given Assumption 2. If FE is fh-IND secure, then FE is  $\mathcal{O}'_{\text{KeyGen}}$ -RUF secure for any  $\gamma < \|\mathbb{F}\|$ .*

*Proof.* Given an adversary  $\mathcal{A}$  in the  $\text{RUF}^{\mathcal{O}'_{\text{KeyGen}}, \gamma}$  game for any  $\gamma < \|\mathbb{F}\|$ , consider the reduction adversary  $\mathcal{R}$ .  $\mathcal{R}$  simulates  $\mathcal{O}'_{\text{KeyGen}}(\mathbf{x}')$  by  $\mathcal{O}_{\text{KeyGen}}(\mathbf{x}', \mathbf{x}')$ .

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**Algorithm 14**  $\mathcal{R}^{\mathcal{O}_{\text{KeyGen}}, \mathcal{O}_{\text{Enc}}}(\text{pp})$

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1:  $\mathbf{r}^{(0)} \leftarrow_{\$} \mathbb{F}^{k+2}$ 
2:  $\mathbf{r}^{(1)} \leftarrow_{\$} \mathbb{F}^{k+2}$ 
3:  $\mathbf{c} \leftarrow \mathcal{O}_{\text{KeyGen}}(\mathbf{r}^{(0)}, \mathbf{r}^{(1)})$ 
4:  $\tilde{\mathbf{z}} \leftarrow \mathcal{A}^{\mathcal{O}'_{\text{KeyGen}}}(\text{pp}, \mathbf{c})$ 
5:  $\mathbf{c}^{(0)} \leftarrow \mathcal{O}_{\text{KeyGen}}(\mathbf{r}^{(0)}, \mathbf{r}^{(0)})$ 
6:  $s \leftarrow \text{FE.Dec}(\text{pp}, \mathbf{c}^{(0)}, \tilde{\mathbf{z}})$ 
7: if  $s \leq \gamma$  then
8:   return  $\tilde{b} = 0$ 
9: else
10:  return  $\tilde{b} \leftarrow_{\$} \{0, 1\}$ 
11: end if

```

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If  $s \neq \perp$ , by Assumption 2, let  $\tilde{\mathbf{z}}$  correspond to a vector  $\tilde{\mathbf{v}}$ .

If the challenge bit  $b = 0$ , then the probability that  $s \leq \gamma$  in Line 7 is

$$\begin{aligned}
\Pr[s \leq \gamma \mid b = 0] &= \Pr[s \neq \perp \mid b = 0] \cdot \Pr[s \leq \gamma \mid b = 0 \wedge s \neq \perp] \\
&= \Pr[s \neq \perp \mid b = 0] \cdot \Pr[\mathbf{r}^{(0)} \tilde{\mathbf{v}}^T \leq \gamma \mid b = 0 \wedge s \neq \perp] \\
&= \Pr[s \neq \perp \mid b = 0] \cdot \Pr[\text{FE.Dec}(\text{pp}, \mathbf{c}, \tilde{\mathbf{z}}) \leq \gamma \mid b = 0 \wedge s \neq \perp]
\end{aligned}$$

By Assumption 2,  $s = \text{FE.Dec}(\text{pp}, \mathbf{c}^{(0)}, \tilde{\mathbf{z}}) \neq \perp$  if and only if  $\text{FE.Dec}(\text{pp}, \mathbf{c}, \tilde{\mathbf{z}}) \neq \perp$  and independent of  $b$ . Hence,

$$\Pr[s \leq \gamma \mid b = 0] = \Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}}, \gamma}(\mathcal{A}) \rightarrow 1]$$

If the challenge bit  $b = 1$ ,

$$\begin{aligned}
\Pr[s \leq \gamma \mid b = 1] &= \Pr[s \neq \perp \mid b = 1] \cdot \Pr[s \leq \gamma \mid b = 1 \wedge s \neq \perp] \\
&= \Pr[s \neq \perp \mid b = 1] \cdot \Pr[\mathbf{r}^{(0)} \tilde{\mathbf{v}}^T \leq \gamma \mid b = 1 \wedge s \neq \perp]
\end{aligned}$$

Note that  $\mathbf{r}^{(0)}$  is independent of  $\tilde{\mathbf{z}}$  and thus  $\tilde{\mathbf{v}}$ , so  $\Pr[\mathbf{r}^{(0)} \tilde{\mathbf{v}}^T \leq \gamma] = \frac{\gamma}{\|\mathbb{F}\|}$  and

$$\Pr[s \leq \gamma \mid b = 1] = \Pr[s \neq \perp \mid b = 1] \cdot \frac{\gamma}{\|\mathbb{F}\|}$$

Again, by Assumption 2,  $s \neq \perp$  if and only if  $\text{FE.Dec}(\text{pp}, \mathbf{c}, \tilde{\mathbf{z}}) \neq \perp$ . Hence,

$$\begin{aligned}
\Pr[s \leq \gamma \mid b = 1] &= \Pr[\text{FE.Dec}(\text{pp}, \mathbf{c}, \tilde{\mathbf{z}}) \neq \perp \mid b = 1] \cdot \frac{\gamma}{\|\mathbb{F}\|} \\
&\geq \Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}}, \gamma}(\mathcal{A}) \rightarrow 1] \cdot \frac{\gamma}{\|\mathbb{F}\|}
\end{aligned}$$

In conclusion,

$$\begin{aligned}
\Pr[\text{fh-IND}(\mathcal{R}) \rightarrow 1] &= \Pr[b = 0] \cdot \left( \Pr[s \leq \gamma \mid b = 0] + \frac{1}{2} \Pr[s > \gamma \mid b = 0] \right) \\
&\quad + \Pr[b = 1] \cdot \frac{1}{2} \Pr[s > \gamma \mid b = 1] \\
&= \frac{1}{2} + \frac{1}{4} (\Pr[s \leq \gamma \mid b = 0] - \Pr[s \leq \gamma \mid b = 1]) \\
&\geq \frac{1}{2} + \frac{1}{4} \left( \Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}, \gamma}}(\mathcal{A}) \rightarrow 1] - \Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}, \gamma}}(\mathcal{A}) \rightarrow 1] \cdot \frac{\gamma}{\|\mathbb{F}\|} \right) \\
&= \frac{1}{2} + \frac{1}{4} \left( 1 - \frac{\gamma}{\|\mathbb{F}\|} \right) (\Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}, \gamma}}(\mathcal{A}) \rightarrow 1])
\end{aligned}$$

Since  $\mathbf{Adv}_{\text{FE}, \mathcal{R}}^{\text{fh-IND}} = |\Pr[\text{fh-IND}(\mathcal{R}) \rightarrow 1] - \frac{1}{2}|$  is negligible,

$$\Pr[\text{RUF}^{\mathcal{O}'_{\text{KeyGen}, \gamma}}(\mathcal{A}) \rightarrow 1] \leq 4 \cdot \left( \frac{\|\mathbb{F}\|}{\|\mathbb{F}\| - \gamma} \right) \cdot \mathbf{Adv}_{\text{FE}, \mathcal{R}}^{\text{fh-IND}} = \text{negl}.$$

□

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