PUF-Based Authentication

PUF-based protocols have been proposed for applications including:

- Encryption and authentication
- For detecting malicious alterations of design components
- For activating vendor specific features on chips

PUFs generate bitstrings that can serve the role of *uniquely identifying the hardware tokens* for authentication applications

With the Internet-of-things (IoT), there are a growing number of applications in which the hardware token is **resource-constrained**

Therefore, novel authentication techniques are required that are *low in cost*, *energy* and *area overhead*

Conventional methods use *area-heavy cryptographic primitives* and *non-volatile memory (NVM)* and are less attractive for these types of embedded applications

PUF-Based Authentication

PUFs are attractive for authentication in **resource-constrained tokens** b/c:

- They *eliminate* (in many proposed authentication protocols) the need for NVM
- A special class of ***strong PUFs*** can also reduce area and energy overheads by reducing the number and type of hardware-instantiated cryptographic primitives
- The application controls the precise generation time of the secret bitstring
- They are *tamper-evident*, i.e., the entropy source of the PUF is sensitive to invasive probing attacks

The tamper-evident and unclonable characteristics of PUFs can be leveraged in authentication protocols to

- Generate *nonces* and *repeatable random bitstrings*
- Provide *secure storage of secrets*
- Reduce *costs* and *energy requirements*
- Simplify *key management*

PUF-Based Authentication

The application defines the requirements regarding the security properties of the PUF

For example, PUFs that produce secret keys for **encryption** are not subject to ***model building attacks*** (as is true for PUF-based authentication)

As discussed, **model building** attempts to 'machine learn' the components of the entropy source as a means of predicting the complete response space of the PUF

This is true for *encryption* because the responses, i.e., the *key*, are not revealed outside the chip

In general, the more access a given application provides to the PUF externally, the ***more resilient*** it needs to be to adversarial attack mechanisms

Authentication as an application for PUFs clearly falls in the category of extended access

Strong PUFs

As discussed earlier, strong PUFs are characterized as having:

- An **exponential challenge space** (note that the response space is not required to be 'exponential')
- **Model-building resistance** (traditionally, ML-resistance was not a requirement, but is now used to distinguish a strong PUF from a *truly* strong PUF)

Given the exposed nature of authentication interfaces, strong PUFs are preferred

However, weak PUFs whose interfaces can be ***cryptographically protected*** are commonly proposed as alternatives

Truly Strong PUFs provide a distinct advantage in authentication protocols

- By reducing the number of *cryptographic primitives*
- While providing high resistance to machine learning and other types of protocol attacks

Intro to PUF-Based Authentication Protocols

Goals of an **authentication protocol**

- Basic: the protocol needs to provide *unilateral*, e.g., server-based, authentication

- Medium: the protocol needs to provide *mutual authentication*

- Advanced: the protocol needs to *preserve privacy* of the token (*privacy-preserving)* This goal is more difficult to achieve, and typically requires additional crypto- graphic primitives and message exchanges

Entity authentication requires the prover (hardware token) to provide both an **identifier** and **corroborative and timely evidence** of its identity

For example, a secret, that could only have been known by the prover itself

PUFs carry out user authentication under the general model of '*something you possess*', e.g., a hardware token such as a smart card

Note that PUFs do not address the task of identifying the user to the token

User-token authentication is handled with passwords, PINs, fingerprints, etc.

Intro to PUF-Based Authentication Protocols

Let's first look at principles and techniques used in PUF-based authentication

And then later look at several protocols that have been proposed which make use of both weak and strong PUFs

Many proposed techniques utilize ***Secure Sketches*** and ***Fuzzy Extractors*** to improve the cryptographic quality of the PUF-generated bitstrings and to improve reliability

These techniques are referred to as **error-correction** and **randomness extraction** mechanism in the literature

There are many forms of error correction that have been developed, mainly in the context of communication protocols

PUF-based methods typically use **helper-data-based algorithms**

Helper data is produced as a supplementary source of information during the initial bitstring generation (**Gen**) process

Helper data is later used to fix bit-flip errors during reproduction (**Rep**) process

Secure Sketches and Fuzzy Extractors

Helper data is typically transmitted and stored **openly**, in a public location

It therefore must reveal as little as possible about the bitstring it is designed to error correct

The *Sketch* component of a **secure sketch** takes an input y, typically the enrollment response bitstring of a PUF, and returns a helper data bitstring w

The *Recover* component takes a *noisy* input y', typically the regenerated response bitstring with bit flip errors, and a helper bitstring w and returns y''

y'' is guaranteed to match the original bitstring y as long as the number of bit flip errors is less than t

t is a parameter that specifies the level of error correction that is needed

A security property can be proved that guarantees that if y is selected from a distribution with **MinEntropy** m

Then an adversary can reverse-engineer y from the helper data w with probability no greater than $2^{-m'}$ (m' is defined below)

Secure Sketches and Fuzzy Extractors

Recall **MinEntropy** refers to the worst-case behavior of a random variable

$$H_{\infty}(X) = min(-\log_2 p_i) = -\log_2(max(p_i)) \quad \textbf{Eq. 1.}$$

Dodis et al. proposed two algorithms for a **secure sketch**, both based on binary error-correcting **linear block codes**

Y. Dodis, L. Reyzin, A. Smith, "Fuzzy Extractors: How to Generate Strong Keys from Biometrics and Other Noisy Data", *Advances in cryptology* (EUROCRYPT), 2004, pp. 523-540.

Y. Dodis, R. Ostrovsky, L. Reyzin, A. Smith, "Fuzzy Extractors: How to Generate Strong Keys from Biometrics and Other Noisy Data", *SIAM Journal on Computing*, 38(1), 2008, 97-139.

A **linear block code** is characterized with three parameters given as [n, k, t], which indicate that there are 2^k codewords of length n

Here, each *codeword* is separated from all others by at least *2t-1* bits

The last parameter specifies the *error correcting capability* of the linear block code, in particular, that up to t bits can be corrected

Secure Sketches and Fuzzy Extractors (derived from Maes text)

The first *linear block code* is called the **code-offset** construction

The *Sketch(y)* procedure samples a uniform, random codeword c (which is independent of y) and produces an n-bit helper data bitstring w

Eq. 2 shows that a simple XOR relationship defines the relationship of the 3 variables

$$w = y \oplus c \qquad \textbf{Eq. 2.}$$

Recover(y', w) computes a noisy codeword c' using Eq. 3 and then applies an error-correcting procedure to correct c' as $c'' = Correct(c')$

$$c' = y' \oplus w \quad => \quad c' = (y \oplus y') \oplus c \qquad \textbf{Eq. 3.}$$

The error-corrected value of y' is computed as given by Eq. 4

$$y'' = w \oplus c'' = y \oplus (c \oplus c'') \qquad \textbf{Eq. 4.}$$

If the number of bits **that are different** between c and $c' < t$, where t represents the error-correcting capability of the code, then the algorithm guarantees $y = y''$

Secure Sketches and Fuzzy Extractors

Also, w discloses at most n bits of y, of which k are **independent** of y (with $k <= n$)

Therefore, the *remaining* MinEntropy m' is the base MinEntropy m minus $(n - k)$, where $(n\text{-}k)$ represents the MinEntropy *that is lost* by exposing w to the adversary

The second algorithm is referred to as the **syndrome** construction

The *Sketch(y)* procedure produces an $(n\text{-}k)$-bit helper data bitstring using the operation specified by Eq. 5, where H^T is a parity-check matrix dimensioned as $(n\text{-}k)$ by n

$$w = y \bullet H^T \qquad \textbf{Eq. 5.}$$

The *Recover* procedure computes a syndrome s using Eq. 6

$$s = y' \bullet H^T \oplus w \quad => \quad s = (y \oplus y') \bullet H^T \qquad \textbf{Eq. 6.}$$

Error correction is carried out by finding a unique error word e such that the *hamming weight* in bitstring e is <= to t (the error correction capability of the code)

$$s = e \bullet H^T \quad \text{with error corrected PUF output} => \quad y'' := y' \oplus e \qquad \textbf{Eq. 7.}$$

Secure Sketches and Fuzzy Extractors

In both the code-offset and syndrome techniques, the *Recover* procedure is more computationally complex than the *Sketch* procedure

The first PUF-based authentication protocols implemented the *Recover* procedure on the resource-constrained hardware token

Subsequent work proposes a **reverse fuzzy extractor**, which implements *Sketch* on the hardware token and *Recover* on the resource-rich server

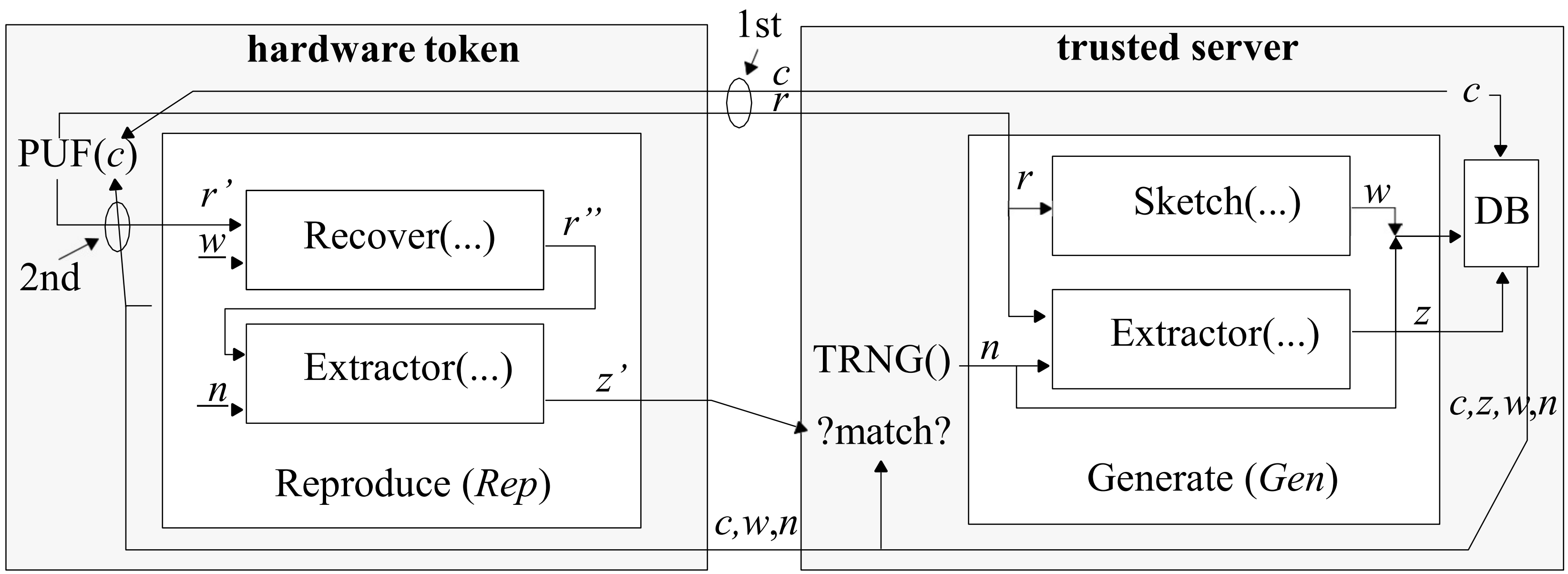
- This makes the protocol more *cost-effective* and *attractive* for this type of application environment

Similar to error-correction, there is a broad range of techniques for constructing a **randomness extractor**

- The Maes text provides a survey of techniques

Fuzzy extractors combine a secure sketch with a randomness extractor

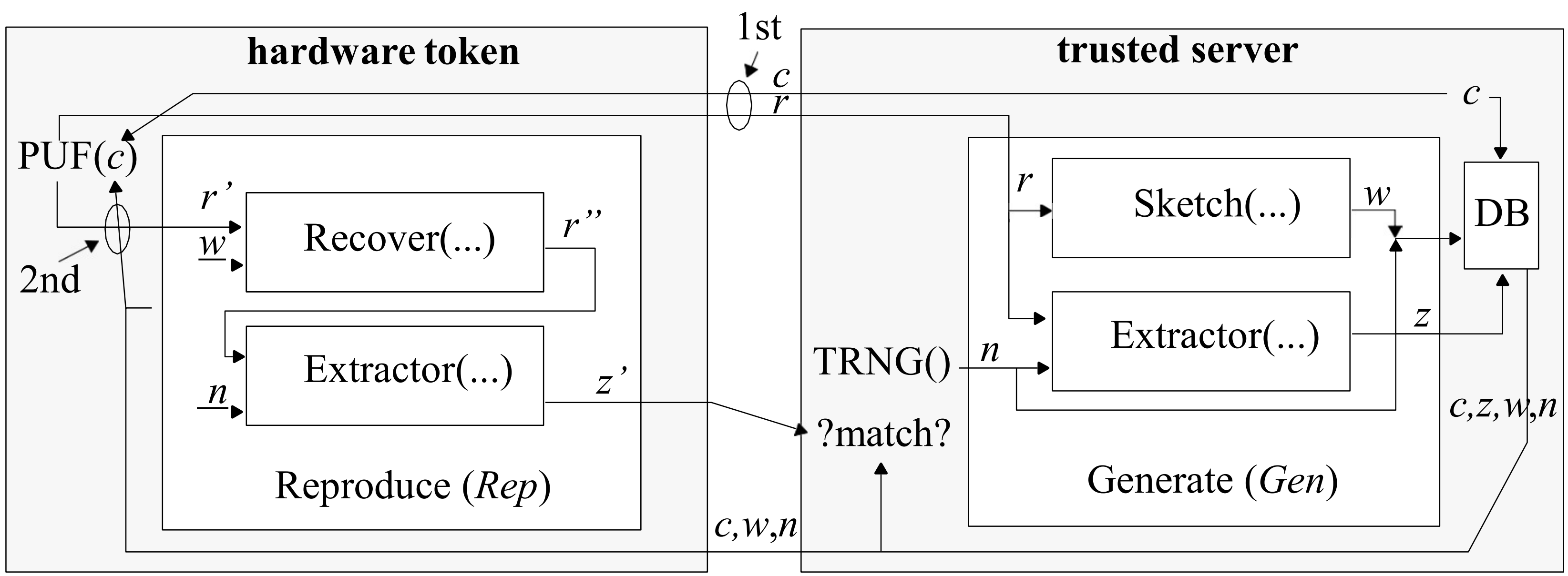
Secure Sketches and Fuzzy Extractors (modified from Maes text)



This PUF-based authentication protocol shows the *hardware token*, e.g., smart card, shown on the left and the *secure server*, e.g., bank, shown on the right

The *Sketch* takes an input *r*, which, e.g., might be a PUF response to a server-generated challenge *c*, as input and produces helper data *w* (labeled *1st* in the figure)

Secure Sketches and Fuzzy Extractors

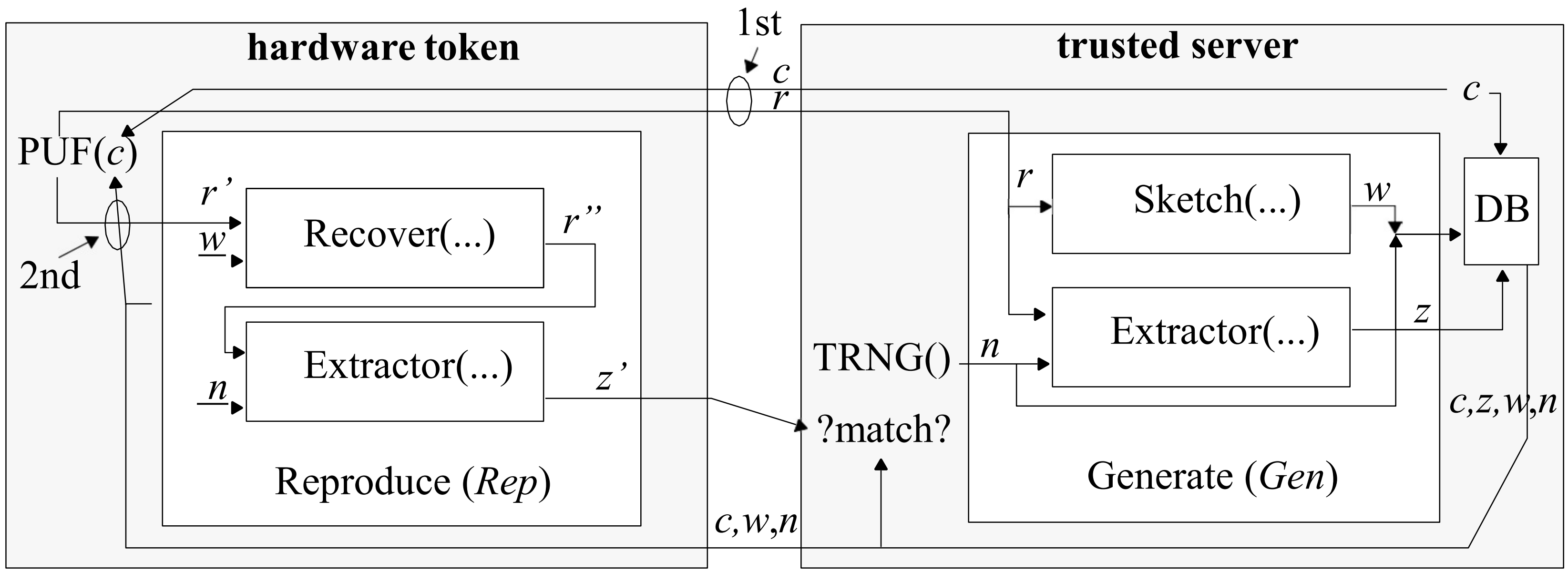


The *Extractor* takes both *r* and a random number (seed) *n* and produces an *entropy distilled* version *z*

This information can be stored as a *tuple* (*c*, *z, w, n*) in a secure database (DB) on the server

This component of the fuzzy extractor is called Generate or *Gen*

Secure Sketches and Fuzzy Extractors

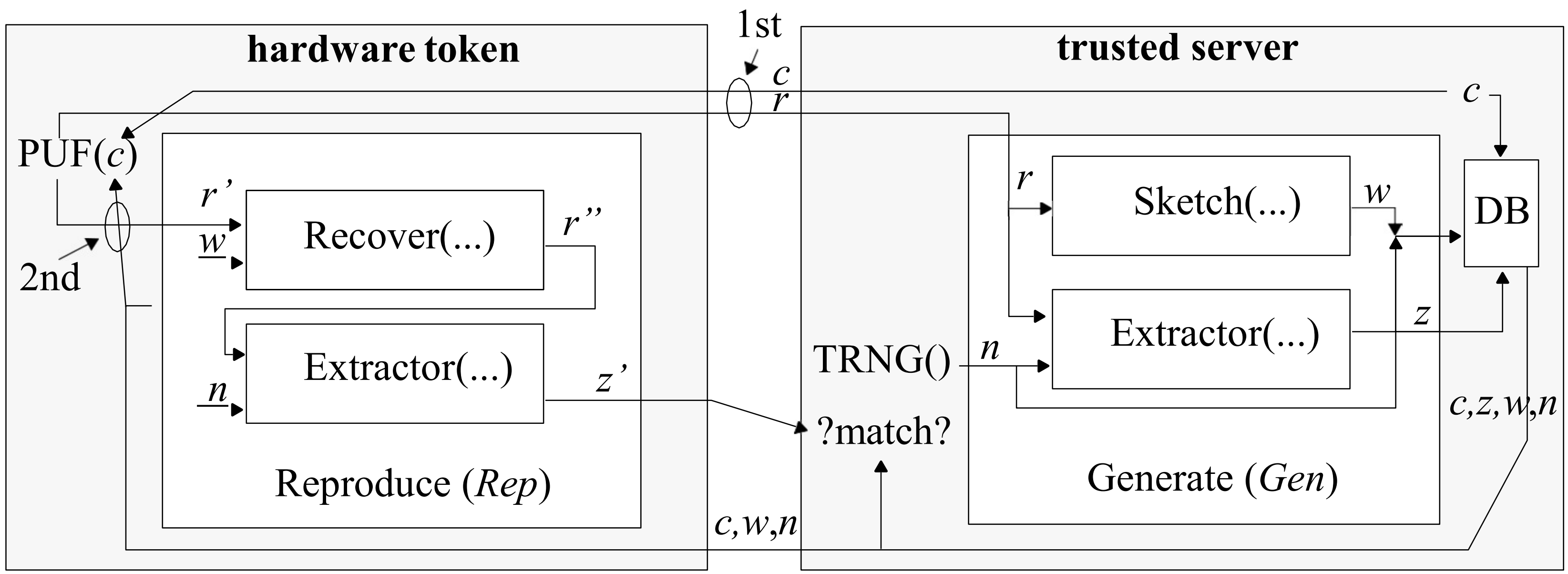


Authentication in the field begins by selecting a tuple (*c*, *z*, *w*, *n*) from the DB and transmitting the challenge *c*, helper data *w* and the seed *n* to the hardware token

The PUF is challenged a second time with challenge *c* and produces a 'noisy' response *r'* (labeled *2nd* in the figure)

The Reproduce or *Rep* process of the fuzzy extractor uses the Recover procedure of the secure sketch to error correct *r'* using helper data *w*

Secure Sketches and Fuzzy Extractors



The output *r''* of Recover and the seed *n* are used by the Extractor to generate *z'*

As long as the number of bit flip errors in *r'* is less than *t* (the chosen error correction parameter), the *z'* produced by the token's Extractor will match the server-DB *z*

And authentication succeeds

Note that the **error corrected** *z'* establishes a shared secret between the server and token, which can alternatively be used as input to hash and block cipher functions