Low-complexity and Reliable Transforms for Physical Unclonable Functions

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Motivations for Physical Identifiers

- Secure secret-key storage and execution in Non-volatile Memory (NVM) are not trivial due to
  - non-uniform key generation,
  - possible physical access to the storage medium,
  - information leakage via side channels.

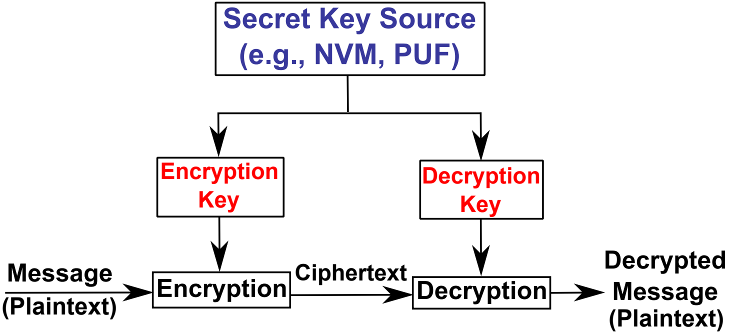
Motivations for Physical Identifiers (Cont'd)

- Alternative: **Physical unclonable functions (PUFs)** such as fine variations in the oscillation frequency of ring oscillators (ROs) for **on-demand** key generation so that
  - invasive attacks permanently change the identifier output,
  - randomness is provided by uncontrollable manufacturing variations,
  - new identifiers can be inserted when there is leakage.

PUF Application 1

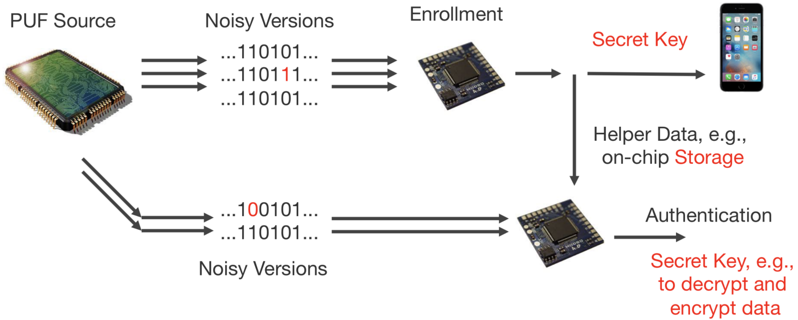
- **Encryption/Decryption with Physical Unclonable Functions (PUFs)**

NVM= Non-Volatile Memory

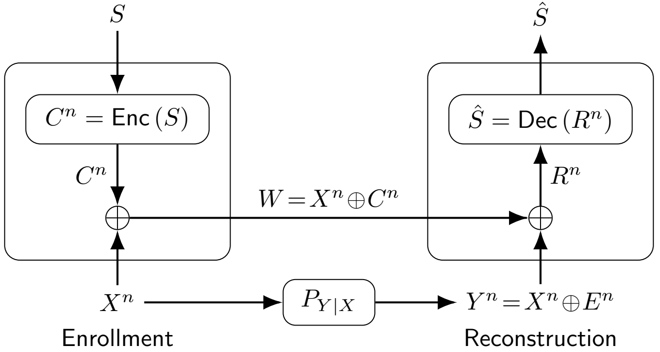


PUF Application 2

- **PUF Outputs Used As a Local Key for a Digital Device**

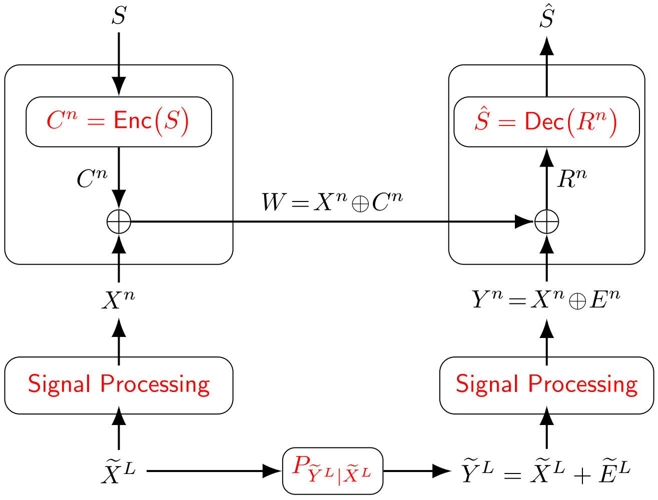


Fuzzy Commitment Scheme (FCS)



- *Secret key* S and *helper data* W have to be **independent**,
- *Block error probability* should satisfy $\mathbf{P_B} = \Pr[\mathbf{S} \neq \hat{\mathbf{S}}] \leq \mathbf{10^{-9}}$,
- S should be **uniformly random** with **entropy of 128 bits**.

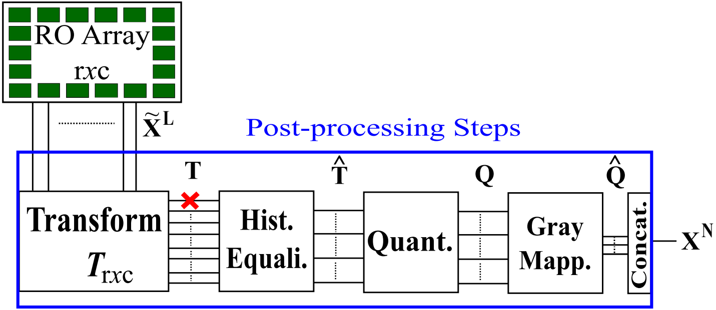
Main Contributions



Main Contributions (Cont'd)

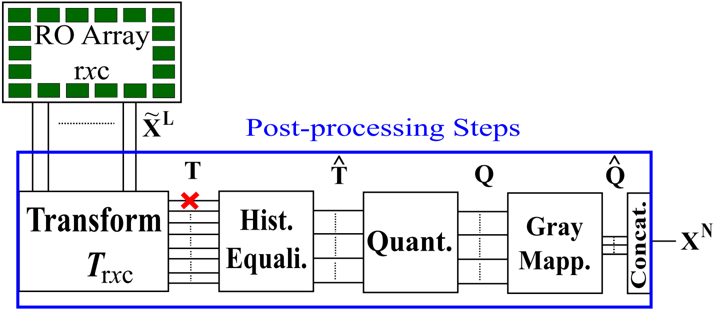
- Propose a new **set of 2D orthogonal transforms** that **simultaneously**
  - provide high decorrelation efficiency (i.e., **small secrecy and privacy leakage**);
  - increase reliability significantly (i.e., **smaller bit error probability**);
  - decrease hardware complexity (i.e., **smaller hardware area due to No Multiplications**);
  - obtain significantly smaller block-error probability $\mathbf{P_B << 10^{-9}}$ than previous FCS designs with the same or smaller channel code rate.

Transform Coding Steps



- Apply a transform $T_{r\times c}(\cdot)$ to **decorrelate** $\widetilde{X}^L/\widetilde{Y}^L$,
- Each scalar quantizer satisfies the **uniformity** property $\Pr[\text{Quant}(\widehat{T}_i) = (q_1, q_2, \dots, q_{K_i})] = \frac{1}{2^{K_i}}$ for $i = 1, 2, \dots, L$,

Transform Coding Steps (cont'd)



- The noise components have zero mean, so use Gray mapping,
- Concatenate all extracted bits to obtain X^n/Y^n,
- Error symbols $E_i = X_i \oplus Y_i$ need not be independent or identically distributed (i.i.d.).

New Set of Transforms

- Consider an orthogonal matrix A with elements 1 or -1 and of size $k \times k$, i.e., $AA^T = I$.

- The following matrices are also orthogonal:

$$\begin{bmatrix} A & A \\ A & -A \end{bmatrix}, \begin{bmatrix} A & A \\ -A & A \end{bmatrix}, \begin{bmatrix} A & -A \\ A & A \end{bmatrix}, \begin{bmatrix} -A & A \\ A & A \end{bmatrix}. \tag{1}$$

- Choose $k = 4$ for exhaustive search of matrices A and apply the matrix extension methods in (1) twice to obtain **12288 unique orthogonal transforms of size 16×16 with elements 1 or -1**.

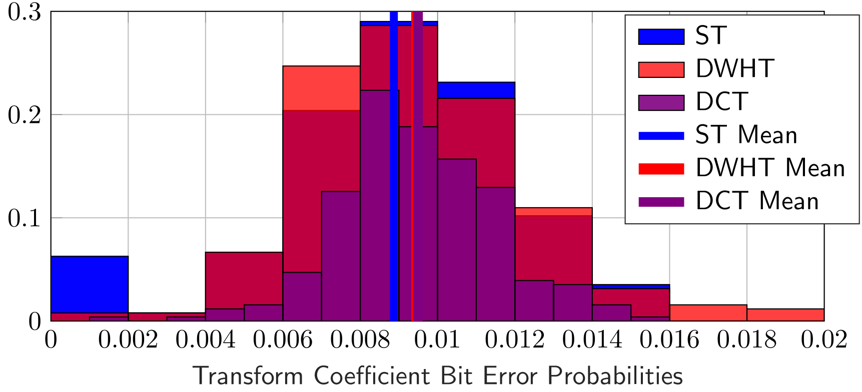
Ring Oscillator Dataset

- We use a public dataset[1] with ring oscillator (RO) outputs.
- The dataset contains multiple measurements of $\mathbf{16}\times\mathbf{16}$ arrays of ROs, e.g., $L = 255$, with identical circuit designs.
- Measurements are taken from multiple devices from **the same chip family** under ideal temperature and voltage conditions.

[1] A. Maiti, J. Casarona, L. McHale, and P. Schaumont, "A large scale characterization of RO-PUF," in *IEEE Int. Symp. on Hardware-Oriented Security and Trust*, Anaheim, CA, USA, June 2010, pp. 94-99.

Bit Error Probabilities

- We compare **bit error probabilities** of the transform coefficients for the selected transform (ST) from the new set, the discrete cosine transform (DCT), and the discrete Walsh-Hadamard transform (DWHT).



Transform Comparisons

- New transforms, including the DWHT, **do not require multiplications (because their transform matrix elements are 1 and -1)**, unlike other transforms, so **the hardware cost is significantly decreased**;

- **Reliability** of the ST is considerably higher than all other transforms;

- All transforms perform well in terms of the **decorrelation efficiency** and pass most of the national institute of standards and technology (NIST) **randomness tests**.

Code Design for the FCS with New Transforms

- **Take advantage of STs' higher reliability** by combining them with *binary linear block codes* with bounded minimum distance decoders (BMDD) for low complexity.

- A BMDD for a block code can **correct all error patterns with at most** $\mathbf{e} = \left\lfloor \frac{\mathbf{d_{min}-1}}{\mathbf{2}} \right\rfloor$ **errors**.

- We use a **Bose-Chaudhuri-Hocquenghem (BCH)** code with blocklength $\mathbf{n = 255 = L}$ bits, code dimension $\mathbf{k = 131 > 128}$ bits, and minimum distance $d_{\text{min}} = 37$ in the FCS.

- This BCH code achieves a block error probability of $\mathbf{P_B \approx 2.860 \times 10^{-12} << 10^{-9}}$,
  which is **the smallest $\mathbf{P_B}$ in the literature** achieved by codes with the same or smaller code rates.

Conclusion

- Proposed a new **set of 2D orthogonal transforms** that **simultaneously** satisfy
  - negligible secrecy leakage;
  - small privacy leakage;
  - large secret key size;
  - small block error probability;
  - low hardware complexity constraints.
- In combination with a BCH code in the FCS, the ST provides **the smallest block error probability in the PUF literature**.

THANK YOU!

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