Effect of Aging on Linear and Nonlinear MUX PUFs by Statistical Modeling

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OUTLINE

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Physical unclonable function (PUFs)

• PUFs are hardware circuits that intrinsically store unique signatures without requiring non-volatile RAMs.
• The unique signature is a result of variations in the manufacturing process.
• For an N-stage MUX PUF: N-bit challenge is Input and 1-bit response is Output. A rising clock edge at the input traverses through the delay chain.

Linear and Nonlinear PUFs

- An N-stage multiplexer (MUX) based PUF has:
  - **Delay chain**: N stages of top and bottom multiplexers.
  - **Arbiter**: A Latch/flip-flop at the end.

- Other configurations like modified feed-forward and feed-forward are formed by adding intermediate arbiters which generate internal challenge bits.

- This makes the PUF structure non-linear in nature.

PUF model for linear MUX PUF

- The response or output can be modelled in terms of the delay-difference of MUX stages.
- Delay-difference of $i^{th}$ stage: $\Delta_i = D_i^t - D_i^b \sim N(0, 2\sigma^2)$
  where $D_i^t, D_i^b$ are the top and bottom multiplexer delays.
- Response bit, $R$, for a linear PUF can be decided based on total delay-difference, $r_N$ as:
  \[
  r_N = \sum_{i=1}^{N+1} (-1)^{C_i} \Delta_i = \sum_{i=1}^{N} (-1)^{C_i} \Delta_i + \Delta^{arb}
  \]
  $C_i = \bigoplus_{j=i}^{N} C_j$ corresponds to delay chain
  $(C_{N+1}=0)$ corresponds to arbiter
  \[
  R = \text{sign}(r_N) = \begin{cases} 
  1, & r_N \geq 0 \\
  0, & r_N < 0
  \end{cases}
  \]
- Delay parameters, $\Delta_i$ and $\Delta^{arb}$ can be estimated using LMS method described in [3].

Authentication of PUFs

**Chip enrollment phase:**
Reference challenge-response pairs (CRPs) are stored as LUT in server. We propose to store model parameters instead (i.e., delay-differences). Needs much less area compared to storing a LUT.

**Authentication phase:**
- Server receives an AUTH request with chip ID from user.
- Selects “random” challenges from database. These are sent to the user and responses are sent back to the server.
- User is granted access if the responses from chip match the responses stored/obtained in the server.
- Certain amount of error can be tolerated.
Authentication of Soft-PUFs

Stability of challenges:

• Due to variations by noise, the response to a challenge can vary upon multiple attempts. In such case, we want to classify challenges as **stable** and **unstable** in terms of their soft-response, $R_s$.

  \[ R_s = \frac{\text{#(number of times response bit is 1)}}{\text{total measurements}} \]

• Thresholds are defined to determine stability – If $R_s < 0.1$ or $R_s > 0.9$, challenge is termed **stable**, otherwise **unstable**.

• During authentication phase, it is desirable to select challenges that are stable.

Total delay-difference distribution

\[ r_N = \sum_{i=1}^{N+1} (-1)^i \Delta^i = \sum_{i=1}^{N} (-1)^i \Delta^i + \Delta_{arb} \]

- % unstable challenges for feed-forward is much higher than linear – for example, 15% vs 11% (for chip-1)
- Standard deviation (\( \sigma \)) of total delay-difference, \( r_N = 0.77 \) (for chip-1)
AGING MODEL

• Aging is caused by undesirable changes in hardware structure such as NBTI (Negative Bias Temperature instability), HCI (hot carrier injection) and TDDB (time dependent dielectric breakdown).

• NBTI happens continuously when the circuit is powered on, whereas HCI only when the circuit has some activity.

• NBTI and HCI cause progressive slowdown in hardware and therefore, increase delays of hardware like MUX.

• Work in [5] showed that variance of delay-differences of delay chain increases with aging, whereas mean of delay-difference can increase or decrease.

• However, variations in delay-difference of the delay chain and arbiter delay is modeled in a slightly different manner.

The delays of multiplexers increase with aging. However, the delay-difference can increase or decrease depending on whether the top or bottom multiplexer increases more.

- The percent delay-difference variation, $p_i$, is modeled as a Gaussian with zero mean and variance increasing with aging [6].
- New delay-difference is expressed as:

$$\Delta_{aged}^i = \Delta^i \left(1 + \frac{\Delta_{aged}^i - \Delta^i}{\Delta^i}\right) = \Delta^i (1 + p_i)$$

Aging model for arbiter

- Arbiter is modeled in terms of its propagation delay (or clock-to-output time).
- However, unlike delay-differences, the arbiter delay takes positive value and therefore, has a positive mean.
- The percent variation, $q$, of arbiter delay is modeled as a Gaussian with positive mean and variance increasing with aging. Arbiter delay with aging is expressed as:

$$\Delta_{aged}^{arb} = \Delta^{arb} (1 + q)$$

- Arbiter ages in an asymmetric fashion [3] – the % variation, $q$, will be much higher than for delay-difference, $p_i$. 
Combined Aging Model

• Environmental noise is added to account for variations in delay parameters.
• Total delay-difference with noise accounted for:

\[ r_N = \sum_{i=1}^{N+1} (-1)^i C_i \Delta_i + \sum_{i=1}^{N+1} n_i \]

**Model assumptions:**
• Under a fixed environmental condition, the effect of noise is static (i.e., noise variance remains fixed).
• Variance of percent variations, \( p_i \) and \( q \), increases with aging.
• For a fixed amount of aging, we can assume that the variance of \( q > p_i \).
Monte-Carlo simulation for aging

- The original delay parameters are estimated using the LMS method for un-aged PUF.

<table>
<thead>
<tr>
<th>Delay Chain</th>
<th>Arbiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta_{aged}^i = \Delta^i (1 + p_i)$</td>
<td>$\Delta_{aged}^{arb} = \Delta^{arb} (1 + q)$</td>
</tr>
<tr>
<td>$\Delta^i$ estimated from original PUF</td>
<td>$\Delta^{arb}$ estimated from original PUF</td>
</tr>
<tr>
<td>1000 $p_i$ samples from Gaussian with zero mean and STD($p_i$)</td>
<td>1000 $q$ samples from Gaussian with positive mean, $\mu$ and STD($q$); $\mu^2 = 3 Var(q)$</td>
</tr>
</tbody>
</table>

- **Equal aging scenario**: when variation in delay chain and arbiter is assumed same/similar, i.e., STD($p_i$) = STD($q$).

- **Unequal aging scenario**: when variation in arbiter is more than delay chain, i.e., STD($q$) > STD($p_i$). Due to asymmetric aging of arbiter, this scenario is more likely.
Performance Metrics

• **Reliability or intra-chip variation**
  - Authentication accuracy: % of responses which match with original responses.
  - Divergence between stable-0 and stable-1 distributions using divergence metrics like Jensen-Shannon (JSD) and Henze-Penrose (HPD).

• **Uniqueness or inter-chip variation** – how different are the responses of each PUF. Uniqueness improves due to random nature of aging.

• **Randomness** – ability to generate unbiased 0 or 1 as response bit. Randomness decreases due to increase in number of 1s with aging.

• **Experimental results are presented for a 32-stage Soft-PUF.**
Reliability: Authentication Accuracy (Equal aging)

- Percent variation considers equal variation in both $p_i$ and $q$.
- **Reliability**: Linear > Modified FF > FF
- **Randomness** decreases as number of bit-flips Stable-$0$--$1$ are higher than Stable-$1$--$0$ for all 3 configs.
- Example: Feed-forward has 11.3% Stable-$0$--$1$ and 9.3% Stable-$1$--$0$
Reliability: Authentication Accuracy (Equal aging)

AGING vs NOISE

%\text{-}authentication is more degraded in case of aging-alone than noise-alone.

However, the degradation is not significant.

Example:
%\text{-}authentication for FF with 20% STD(p,q) is 94.63%, whereas with 20% STD(noise) is 95.28%.

The difference between their performance is only 0.65%.

\begin{table}[h]
\centering
\caption{Percentage Successful Authentication under equal aging scenario; $\text{STD}(q)=\text{STD}(p_i)$}
\begin{tabular}{|c|c|c|c|c|}
\hline
\% STD & No Noise & Noise STD=5\% & Noise STD=10\% & Noise STD=20\% \\
\hline
\hline
\textbf{Linear} & \textbf{Original} & 0.9993 & 0.9980 & 0.9930 & 0.9729 \\
 & 5\% & 0.9981 & 0.9967 & 0.9917 & 0.9714 \\
 & 10\% & 0.9927 & 0.9911 & 0.9860 & 0.9674 \\
 & 20\% & 0.9697 & 0.9683 & 0.9639 & 0.9487 \\
\hline
\textbf{MFF} & \textbf{Original} & 0.9985 & 0.9974 & 0.9921 & 0.9710 \\
 & 5\% & 0.9977 & 0.9963 & 0.9911 & 0.9698 \\
 & 10\% & 0.9923 & 0.9906 & 0.9854 & 0.9661 \\
 & 20\% & 0.9690 & 0.9675 & 0.9629 & 0.9486 \\
\hline
\textbf{FF} & \textbf{Original} & 0.9982 & 0.9954 & 0.9863 & 0.9528 \\
 & 5\% & 0.9955 & 0.9927 & 0.9837 & 0.9523 \\
 & 10\% & 0.9842 & 0.9817 & 0.9728 & 0.9450 \\
 & 20\% & 0.9463 & 0.9442 & 0.9387 & 0.9187 \\
\hline
\end{tabular}
\end{table}
Reliability: Authentication Accuracy (Unequal aging)

- Authentication accuracy with aging considered for delay chain and arbiter separately is shown.
- We expect $\text{STD}(q) > \text{STD}(p_i)$ degradation due to arbiter becomes much more significant than due to delay chain.
Reliability: Authentication Accuracy (Unequal aging)

AGING vs NOISE

- %-authentication is more degraded in case of aging-alone than noise-alone.
- However, the degradation in this case is much more significant.

Example:
- %-authentication for FF with 20% STD($p_i$), 40% STD(q) is 91.36%, whereas with 20% STD(noise) is 95.28%.
- The difference between their performance now is 3.92%.

### TABLE II
Percentage Successful Authentication under unequal aging scenario; $STD(q) = STD(p_i) + 20\%$

<table>
<thead>
<tr>
<th>% $STD(p,q)$</th>
<th>No Noise</th>
<th>Noise STD=5%</th>
<th>Noise STD=10%</th>
<th>Noise STD=20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,20)</td>
<td>0.9961</td>
<td>0.9941</td>
<td>0.9892</td>
<td>0.9704</td>
</tr>
<tr>
<td>(5,25)</td>
<td>0.9914</td>
<td>0.9898</td>
<td>0.9843</td>
<td>0.9657</td>
</tr>
<tr>
<td>(10,30)</td>
<td>0.9825</td>
<td>0.9805</td>
<td>0.9761</td>
<td>0.9594</td>
</tr>
<tr>
<td>(20,40)</td>
<td>0.9568</td>
<td>0.9556</td>
<td>0.9526</td>
<td>0.9409</td>
</tr>
<tr>
<td>MFF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,20)</td>
<td>0.9960</td>
<td>0.9944</td>
<td>0.9891</td>
<td>0.9694</td>
</tr>
<tr>
<td>(5,25)</td>
<td>0.9912</td>
<td>0.9896</td>
<td>0.9848</td>
<td>0.9663</td>
</tr>
<tr>
<td>(10,30)</td>
<td>0.9827</td>
<td>0.9815</td>
<td>0.9761</td>
<td>0.9592</td>
</tr>
<tr>
<td>(20,40)</td>
<td>0.9566</td>
<td>0.9561</td>
<td>0.9528</td>
<td>0.9391</td>
</tr>
<tr>
<td>FF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0,20)</td>
<td>0.9795</td>
<td>0.9773</td>
<td>0.9700</td>
<td>0.9441</td>
</tr>
<tr>
<td>(5,25)</td>
<td>0.9672</td>
<td>0.9654</td>
<td>0.9591</td>
<td>0.9354</td>
</tr>
<tr>
<td>(10,30)</td>
<td>0.9506</td>
<td>0.9494</td>
<td>0.9433</td>
<td>0.9248</td>
</tr>
<tr>
<td>(20,40)</td>
<td>0.9136</td>
<td>0.9124</td>
<td>0.9096</td>
<td>0.8937</td>
</tr>
</tbody>
</table>
Reliability: Divergence Metrics
Total delay-difference distribution of stable 0 and stable 1

• Ideally, there should be no overlap between the stable 0 and stable 1 distributions – represents error/noise of the model.
• With aging, as delay parameters start to vary, the overlap between these distributions increase.
• This overlap reflects the bit-flips occurring in the responses of these challenges.
• Metrics like Jensen-Shannon, Henze-Penrose divergence are used to analyze these overlaps.

Probability distributions for unaged linear MUX PUF
Reliability: Divergence Metrics

- **Jensen-Shannon divergence**: symmetric form of KL divergence. KL divergence was found to be sensitive to low values of probability.

\[
JS(P||Q) = \frac{1}{2} (KL(P||R) + KL(Q||R)),
\]

where \( R = \frac{1}{2} (P + Q) \)

- **Henze-Penrose divergence** [7]: Randomly sample \( r_N \) from a set of \( r_N \) values obtained for an equal number of Stable-0 and Stable-1 CRPs. Sort them in increasing/decreasing order and count the number of differing classification, \( R \) out of total \( N \). HPD is computed as: \( HPD = 1 - R / N \)

![Diagram showing probability distributions for Stable 0 and Stable 1 with HPD computed as 30%](image)

\[
STD(q) = STD(p_i) = \frac{STD(n_i)}{STD(A_i)} = 30\%
\]

Probability distributions with 30% variation due to aging/noise

Reliability: Divergence Metrics

- Dashed lines show the performance in case of **noise-alone** and solid line for the case of **aging-alone** scenario.
- A lower divergence value corresponds to a higher overlap between the Stable-0 and Stable-1 distributions.
- Range of JSD is 0-1 and HPD is 0.5-1.
Improving reliability

• **Recalibration**: The delay parameters can be recalibrated using LMS method. But not feasible as thousands of devices will need to be recalibrated.

• **Tuning a threshold** based on total delay-difference, $r_N$:
  - Challenges with $r_N$ close to 0 are more prone to aging related bit-flips.
  - Therefore, choosing a threshold on $r_N$ will improve the reliability albeit a lower number of available challenges.
  - Higher the threshold, better reliability is guaranteed.
  - However, we do not need 100% reliability as certain error in the responses to the set of challenges is tolerated. Threshold requirement is further lower in this case.
Improving reliability of 32-stage PUF

Plots show % Error in authentication by considering only CRPs with $|r_N| \geq \beta$.

**Example:**
- Error Tolerance = 1.5%, Thresholds for $\text{STD}(p_i) = \text{STD}(q) = 33\%$ (equal) amount of aging - 0.275 for linear, 1.4 for feed-forward.
- # of challenges with $|r_N| \geq \beta$, threshold – $2^{31}$, $2^{26}$ respectively.
Conclusion

• Aging effects of delay chain and arbiter can be modeled in terms of Gaussian distributions.

• Aging degradation is similar (or slightly worse) to that of noise under equal aging scenario. This is because aging and noise are modeled in a similar manner.

• Under the assumption that arbiter “ages” much more significantly than delay chain (unequal aging), the performance degradation due to aging is much more prominent compared to noise.

• The performance degradation due to aging can be improved by tuning thresholds based on total delay-difference. This decreases the number of challenges available for authentication purposes.