The influence of Spatial and Transient Circuit Variations on Energy and Accuracy in Stochastic Computing Circuits

Bert Moons
Marian Verhelst

20/03/2014
Presentation outline

- **Introduction**
- Stochastic Computing (SC)
- Noise sources in SC
- Energy dissipation in SC
- Single stage noise analysis
- Conclusion
Introduction

- Advanced technologies are increasingly unreliable.
- In classic digital circuits, faults caused by unreliability are always prevented:
  - Introduction of energy consuming design margins:
    - Higher supply voltage;
    - Longer delays;
    - Conservative Layout;
    - System redundancy.
**Introduction**

- **Research hypothesis:**
  - By allowing **controllable faults** in digital electronics, the **energy consumption** in fault tolerant applications can be reduced.
  - => No need for energy wasting design margins.

---

**Diagram:**

<table>
<thead>
<tr>
<th>Application</th>
<th>Traditional Digital Design</th>
<th>Alternative Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computing-based</td>
<td>(Deterministic foundations)</td>
<td></td>
</tr>
<tr>
<td>Communication-inspired</td>
<td>(Statistical foundations)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Deterministic Computing – high energy dissipation</th>
<th>Alternative Computing – low energy dissipation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst-case design</td>
<td></td>
<td>Nominal-case design</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>Device Physics (Statistical foundations)</th>
<th>Device Physics (Statistical foundations)</th>
</tr>
</thead>
</table>
Introduction

- **State-of-the-art Literature**
  - Imprecise Hardware (pruning of basic binary arithmetic blocks) [1]
  - Stochastic Computation: class of techniques exploiting probability theory to deal with uncertainty. (e.g. ANT) [2]

- **Stochastic Computing** [3]

Presentation outline

- Introduction
- **Stochastic Computing (SC)**
- Noise sources in SC
- Energy dissipation in SC
- Single stage noise analysis
- Conclusion
Stochastic Computing (SC)

- Type of digital logic in which information is represented and processed in the form of digitized probabilities.
  
  $\begin{align*}
  0 & \quad 1 \\
  1 & \quad 0
  \end{align*}$
  
  $= 2$ in 3 bit parallel $\implies 0,0,1,0,1,0,0,0 \implies p = 2/8$ in 8 bit serial

- $p$ equals the probability of any bit of the bit-stream to equal one.

- This leads to simplified hardware:
Stochastic Computing (SC)

- **UP: Unipolar representation** - $p \in [0,1]$
- **BP: Bipolar representation** - $s = 2p - 1 \in [-1,1]$

![Diagrams of stochastic computing concepts](image)

Stochastic Computing (SC)

Advantages
- Simplified Hardware (highly parallelizable)
- Run-time adaptable precision (easy transition from eg. 8->6 bit precision)
- Inherently fault tolerant (faults on LSB i.s.o. MSB)
  - Binary adder has possible timing errors on MSB
  - Stochastic computation adder only has LSB faults

Disadvantages
- Very long bitstreams (O(2^n))
Case study: SC JPEG compression

- Stochastic computing error tolerance example:
  - Stochastic DCT implementation as part of JPEG encoder

CR = 74.5, RMSE = 12.1%
(a) Binary at $p_t = 1e - 3$

CR = 91.2%, RMSE = 2.3%
(b) SC ($L = 2^{16}$) at $p_t = 1e - 3$
Case Study: SC Edge-detection

- Edge-detection performance under different input noise conditions. [4]

Figure 10. Edge-detection performance for three implementation methods with noise levels of (a) 5%, (b) 10% and (c) 20%.

Paper goal:

- Quantitatively investigate the performance of Stochastic Computation under the influence of different noise sources / uncertainties.

- Performance is measured in terms of **energy** and **accuracy**.
Presentation outline

- Introduction
- Stochastic Computing (SC)
- **Noise sources in SC**
- Energy dissipation in SC
- Single stage noise analysis
- Conclusion
Errors in digital circuits are mainly due to:

| Type I: Inherent inaccuracy | Random in time and space  
|                           | Binary: quantization noise  
|                           | SC: noise due to randomness |
| Type II: Spatial circuit variations | Fixed in time and space  
|                                   | All types of inter- and intra-die variations |
| Type III: Transient circuit variations | Random in time and space |
|                                       | - Random bit-flips;  
|                                       | - Supply voltage ringing;  
|                                       | - Radiation effects. |
Type I: inherent inaccuracy

- Inherent noise in stochastic Computing is binomial:
  \[ \sigma_{\text{mean SC}}^2 = \text{RMSE}^2 = \int_0^1 \frac{p(1-p)}{L} \, dp = \frac{1}{6L} \]

- Binary quantization noise:
  \[ \sigma_{\text{bin}}^2 = \frac{\delta^2}{12} = \frac{1}{12 \cdot 2^{2n}} \]

- Comparison:
  \[ \sigma_{\text{SC}}^2 = \sigma_{\text{bin}}^2 \Leftrightarrow L = 2^{2n+1} \]

\[ \Rightarrow n=4 \Rightarrow L=512 \text{ at equal mean absolute noise} \]
Type II: spatial inaccuracy

- **Dominant** circuit uncertainty
- Should be **tuned out**
  - Random spatial variations are fixed in time and space after production.
  - Faults due to spatial variations become repetitive and deterministic!
Type III: transient inaccuracy

- Can be modelled by extending the stochastic circuitry with XOR-gates at its outputs.

\[ p_{\text{out\_distorted}} = \text{xor}(p_{\text{out}}, \text{distortion rate } p_t) \]
Presentation outline

- Introduction
- Stochastic Computing (SC)
- Noise sources in SC
- **Energy dissipation in SC**
- Single stage accuracy analysis
- Conclusion
Energy dissipation in SC

- Energy scales linearly with bit-stream length $L$
  - $k = \text{Energy/bit-operation} = \text{function of } V \text{ and } f$
  - $L = \text{bit-stream length}$

$$E_{SC} = k \cdot L$$

- Energy in a system suffering from type I errors.

$$E_{SC} = \frac{k}{6 \cdot \text{RMSE}^2}$$
Presentation outline

- Introduction
- Stochastic Computing (SC)
- Noise sources in SC
- Energy dissipation in SC
- **Single stage noise analysis**
- Conclusion
Simulation Set-up

- Tested circuits:
  - Stochastic: Unipolar AND-gate multiplier;
  - Binary: Standard RC-multiplier.

- Comparison is for same overall delay (32ns).
- Supply voltage is swept at given clock freq.
- Minimal supply voltage at which no type II errors occur is used to assess the impact of type I and III errors. \(\rightarrow \) simulated energy/word is the minimal energy.
Single stage noise analysis: type I + type III

\[ pt = \text{transient error rate} \]

Binary lower limit
@ \( pt = 1e^{-3} \)

SC lower limit
@ \( pt = 1e^{-3} \)

RMSE versus binary precision (n) and stochastic length (L)
**Single stage noise analysis: type I + type III**

- **Binary**
  - Invest more energy:
    - $\Rightarrow$ RMSE does not drop

- **SC**
  - Invest more energy:
    - $\Rightarrow$ RMSE drops

- $\Rightarrow$ SC allows to trade-off energy for precision, even when transient errors are present
Single stage noise analysis: type I + type II

- Higher spatial variations:
  - More energy needed to reach given RMSE.

- \[ E_{SC} = \frac{k}{6 \cdot RMSE^2} \]
- \[ E_{bin} = \frac{C}{RMSE^2} \]

- In technologies with very low energy/bit-operation k, SC may outperform binary.
Presentation outline

- Introduction
- Stochastic Computing (SC)
- Noise sources in SC
- Energy dissipation in SC
- Single stage noise analysis
- **Conclusion**
Conclusion

- **Inherent noise** in SC is much larger than in Binary.
- SC greatly outperforms binary logic when transient variations are present. Under these circumstances it can still trade-off energy for precision by using longer bit-streams, while binary logic can not.
- SC may be a good alternative to binary in technologies with a low k (energy per bit-operation) that suffer from significant transient circuit variations.
Thank you!

QUESTIONS?