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

Bert Moons

Marian Verhelst

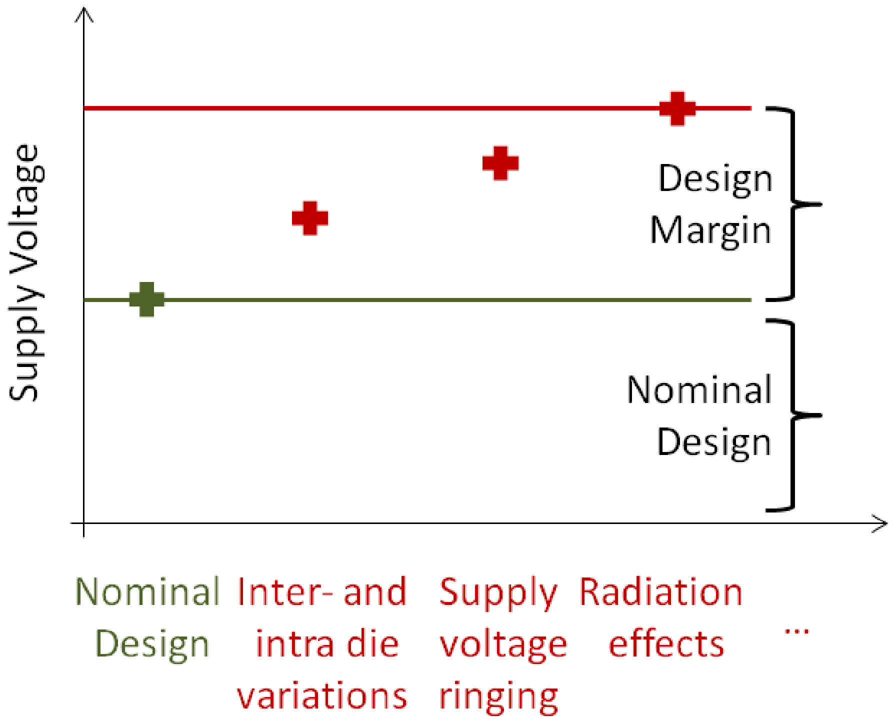
20/03/2014

Presentation outline

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

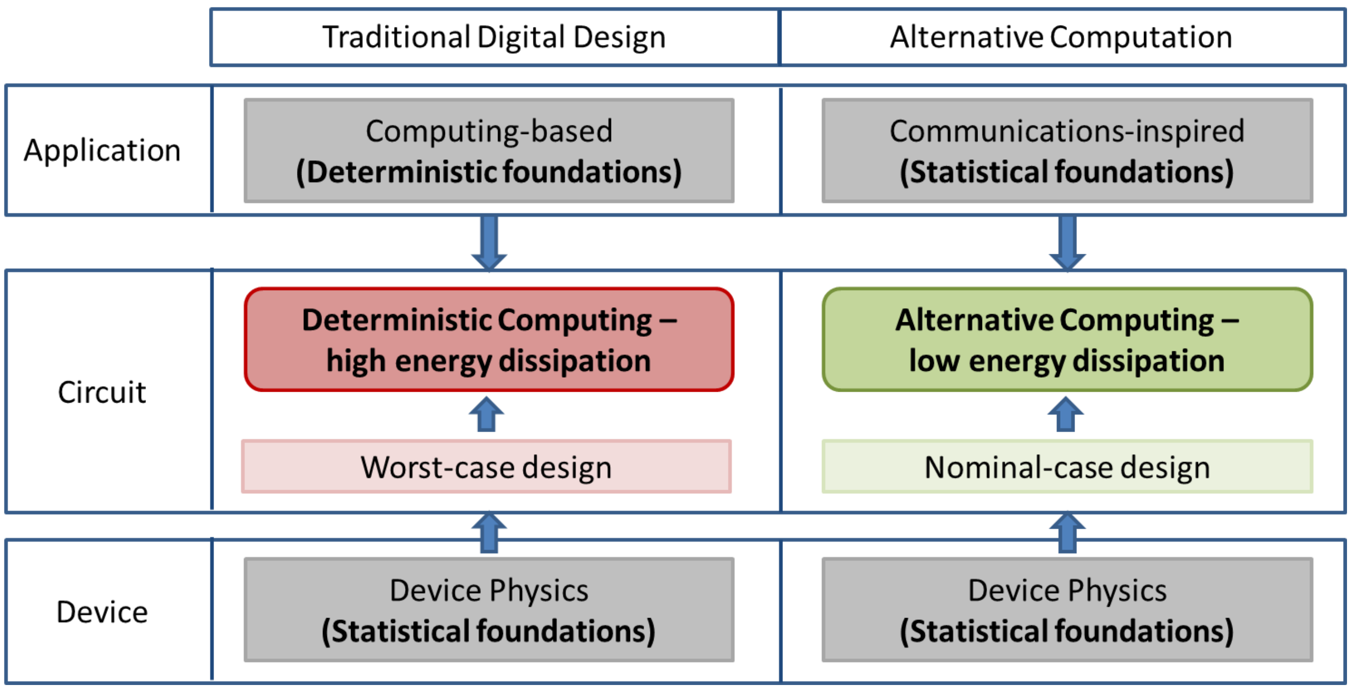
Introduction

- 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.



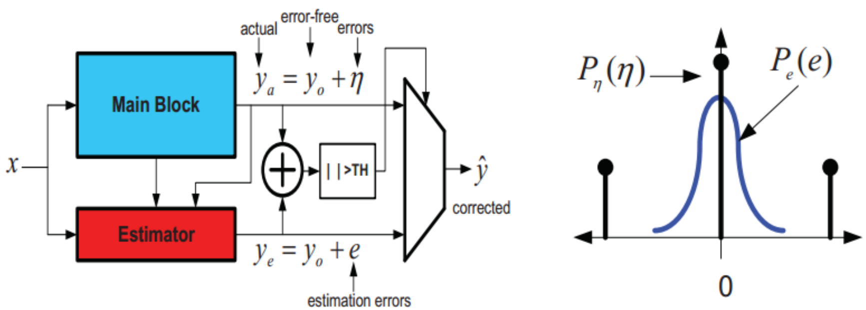
Introduction

- 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.

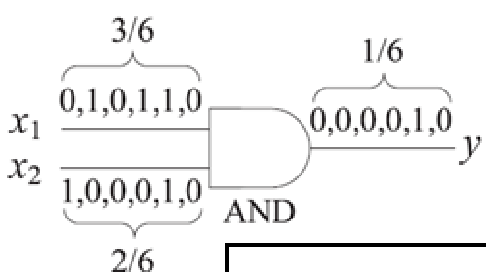


Introduction

- 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]



  - **<u>Stochastic Computing</u>** [3]



$$y = x_1 \cdot x_2$$

[1] = Weber, “Balancing adder for error tolerant applications”, ISCAS, 2013
[2] = Shanbhag,“stochastic computation”,DAC,2010
[3] = Alaghi, A. , Hayes, J., “Survey of stochastic computing”, ACM, 2012

Presentation outline

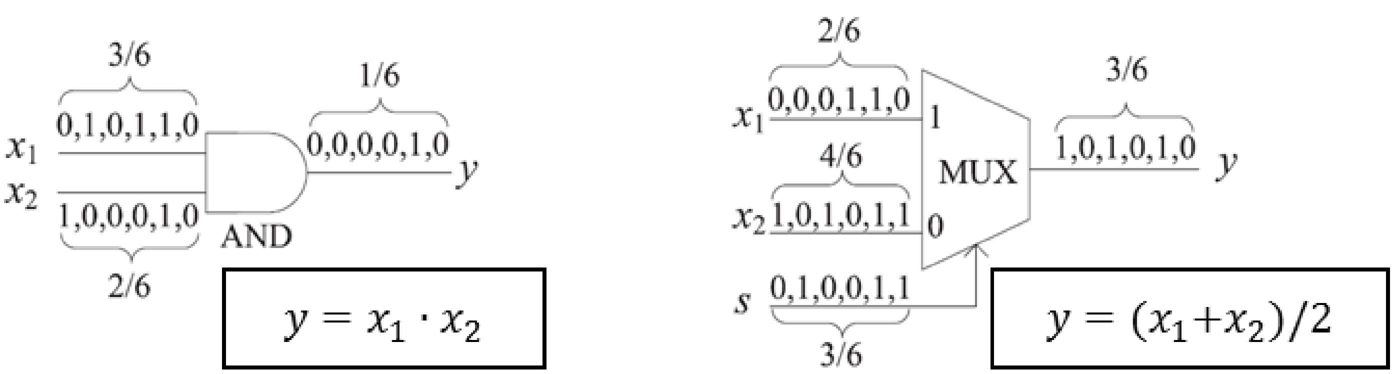
- Introduction
- **Stochastic Computing (SC)**
- Noise sources in SC
- Energy dissipation in SC
- Single stage noise analysis
- Conclusion

Stochastic Computing (SC)

- Type of digital logic in which information is represented and processed in the form of digitized probabilities.

  0
1 = 2 in 3 bit parallel => 0,0,1,0,1,0,0,0 = p = 2/8 in 8 bit serial
0

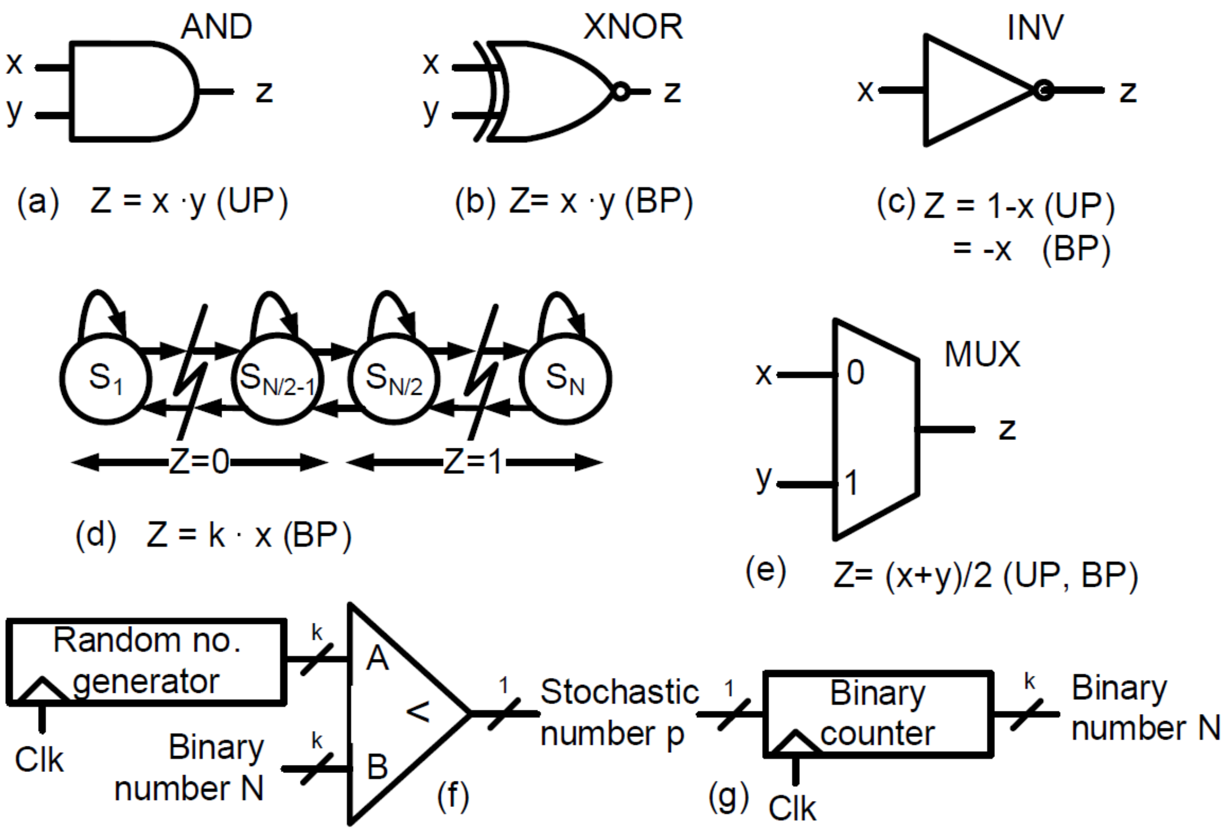
- p equals the probability of any bit of the bit-stream to equal one.
- This leads to simplified hardware:



(a) (b)

Stochastic Computing (SC)

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



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]

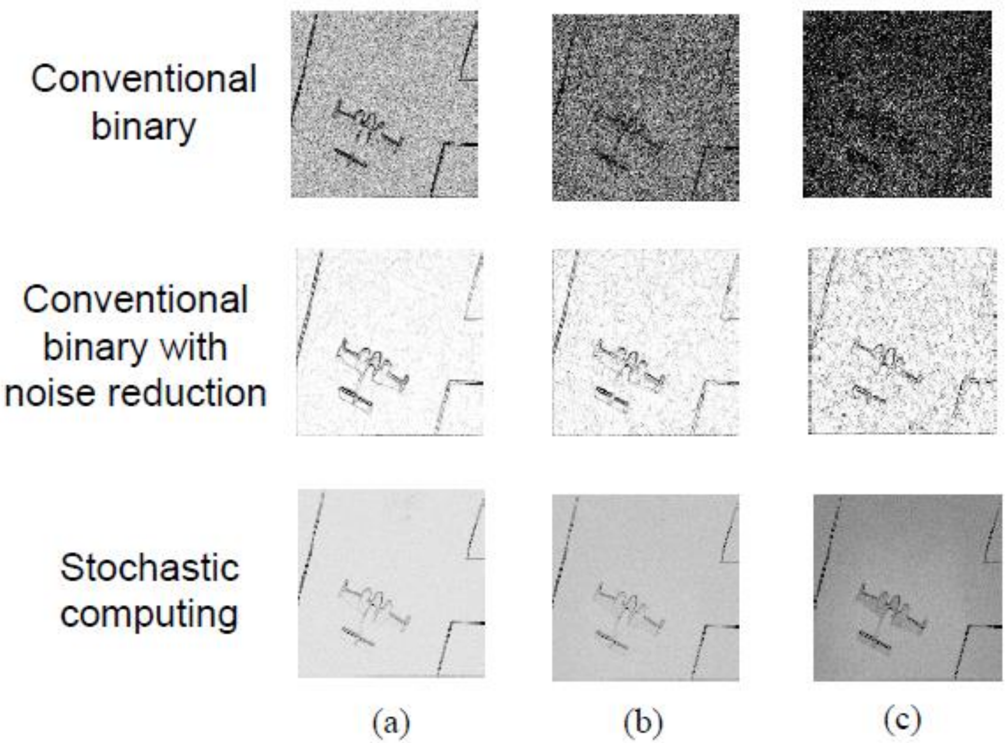


Figure 10. Edge-detection performance for three implementation methods with noise levels of (a) 5%, (b) 10% and (c) 20%.

[4] = Alaghi, A. , Hayes, J.P.,"Stochastic Circuits for Real-Time Image-Processing Applications", DAC,2013.

Stochastic Computing

- 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)
- **<u>Noise sources in SC</u>**
- Energy dissipation in SC
- Single stage noise analysis
- Conclusion

Noise in Stochastic computing

- 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:

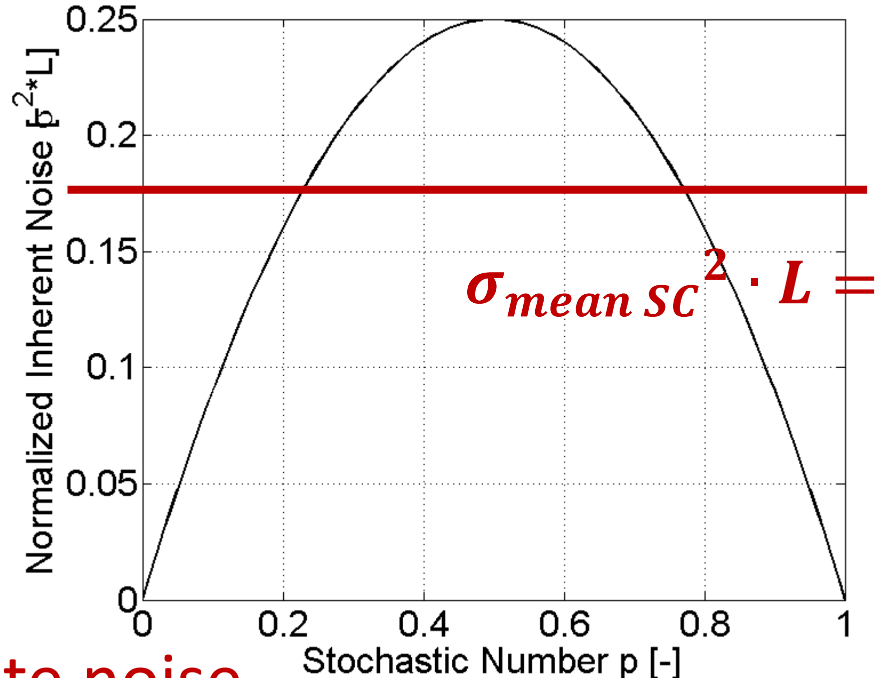
$$\sigma^2_{mean\ SC} = RMSE^2 = \int_0^1 \frac{p(1-p)}{L}\, dp = \frac{1}{6L}$$

- Binary quantization noise:

$$\sigma^2_{bin} = \frac{\delta^2}{12} = \frac{1}{12 \cdot 2^{2n}}$$

- Comparison:

$$\sigma^2_{SC} = \sigma^2_{bin} \Leftrightarrow L = 2^{2n+1}$$



$$\boldsymbol{\sigma_{mean\ SC}}^2 \cdot \boldsymbol{L} = \frac{\mathbf{1}}{\mathbf{6}}$$

⇒ n=4 ⇒ L=512 at equal mean absolute noise

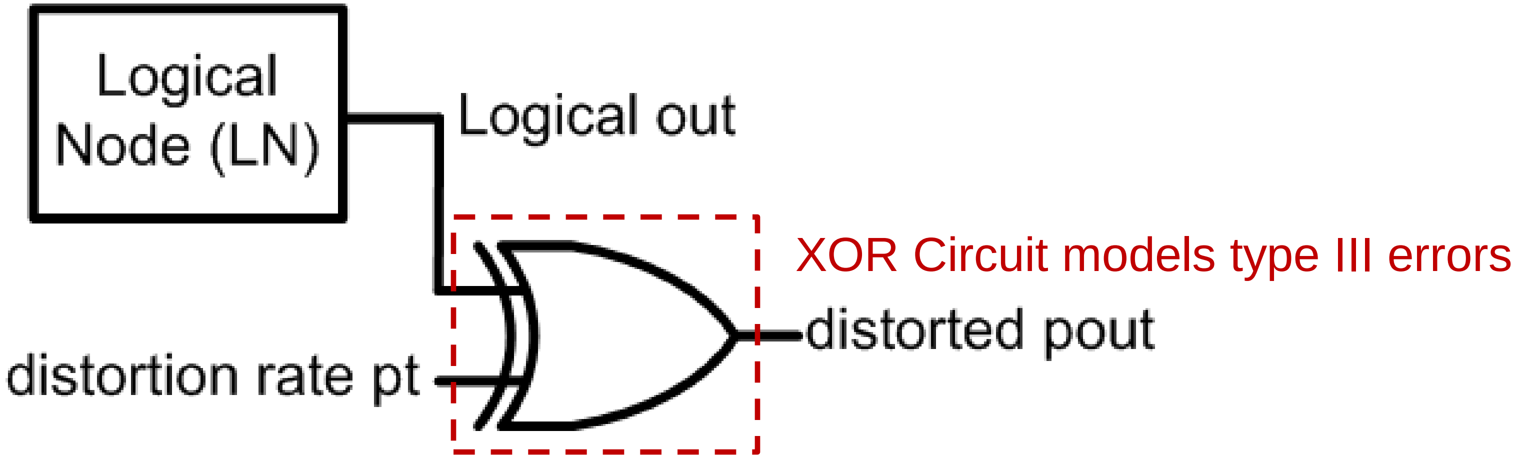
Type II: spatial inaccuracy

- 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.

$$pout_{distorted} = xor(pout, distortion\ rate\ p_t)$$



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 = Energy/bit-operation = function of V and f
  - L = bit-stream length

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

  - Energy in a system suffering from type I errors.

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

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 => simulated energy/word is the minimal energy.

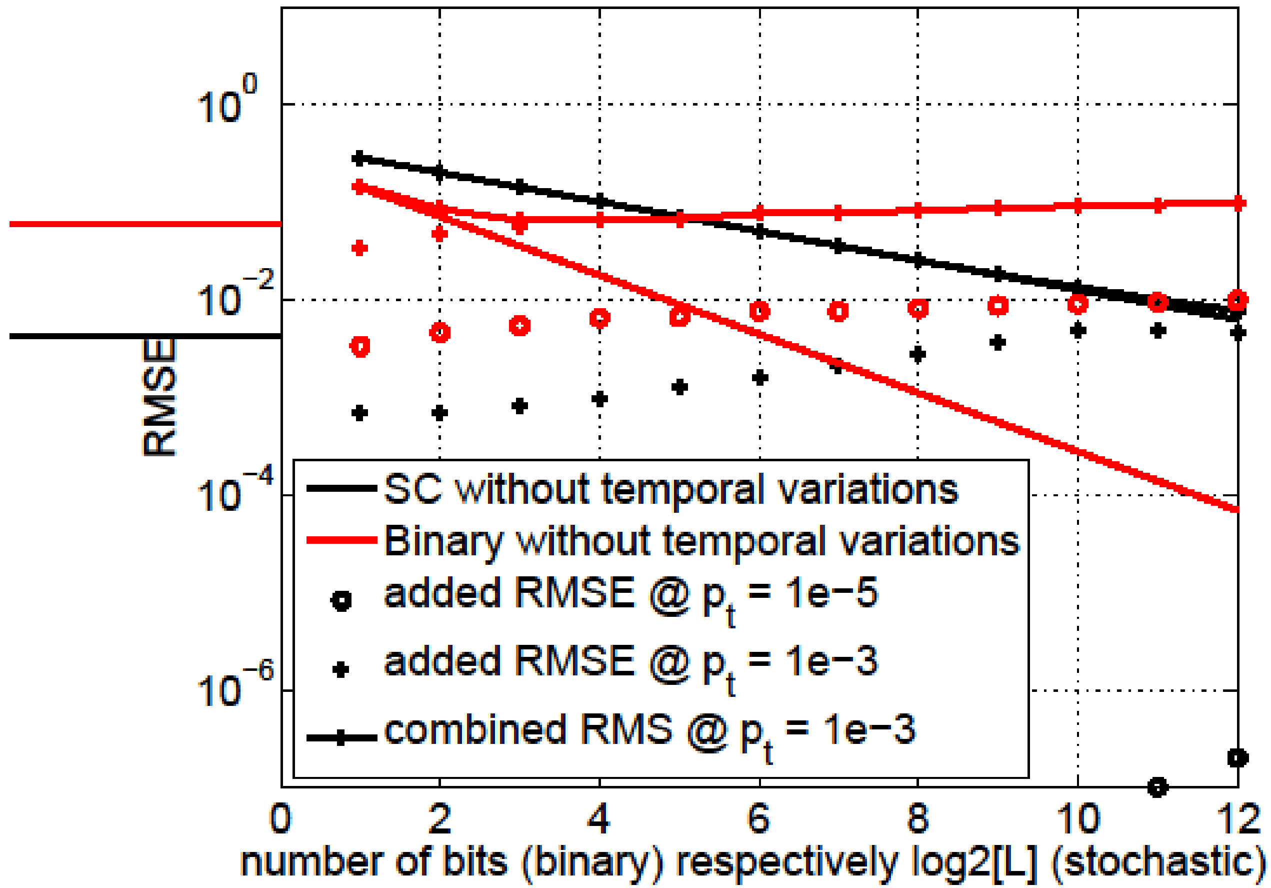
Single stage noise analysis: type I + type III

pt = 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

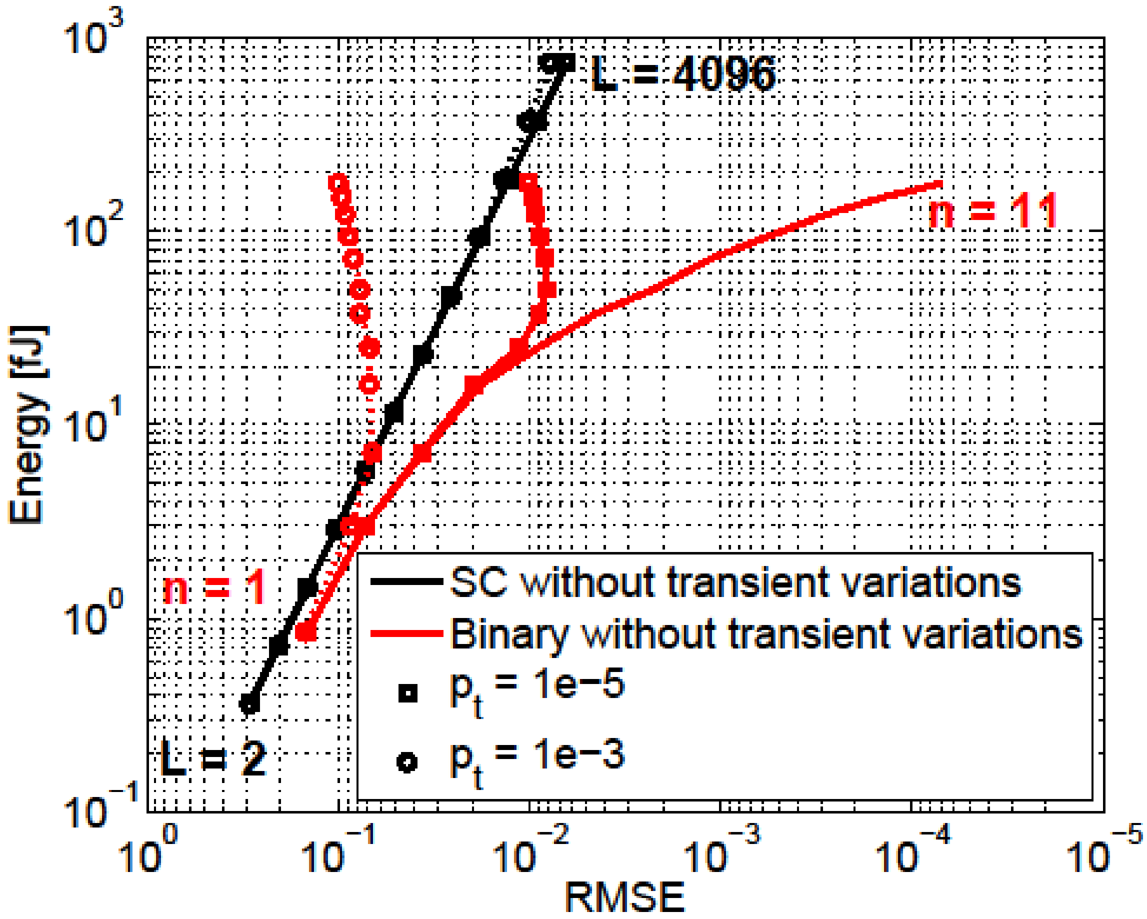
- Binary
  - Invest more energy:

    ⇒RMSE does not drop
- SC
  - Invest more energy:

    ⇒RMSE drops

- ⇒ SC allows to trade-off energy for precision, even when transient errors are present

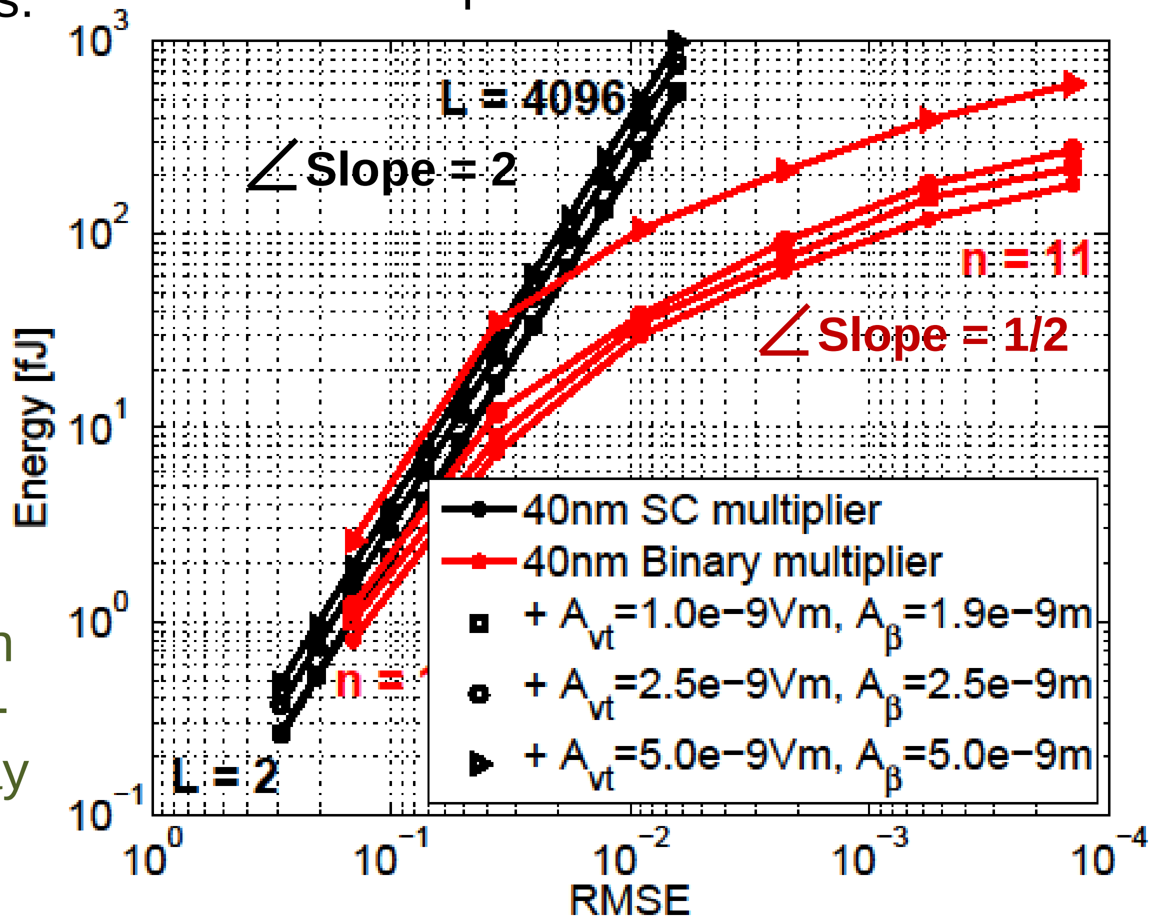
Energy versus RMSE in circuits suffering from transient variations



Single stage noise analysis: type I + type II

- Higher spatial variations:
  - ⇒More energy needed to reach given RMSE.
  - $E_{SC} = \frac{k}{6 \cdot RMSE^2}$
    $E_{bin} = \frac{c}{RMSE^{\frac{1}{2}}}$
  - In technologies with very low energy/bit-operation k, SC may outperform binary.

Energy versus RMSE in circuits suffering from spatial variations



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?