



Circuits for True Random Number Generation with On-Line Quality Monitoring

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Circuits for True Random Number Generation with On-Line Quality Monitoring

Arnaud Tisserand

CNRS, IRISA laboratory, CAIRN research team

Claude Shannon Institute Workshop on Coding & Cryptography
May 23–24, 2011, UCC

- Motivations and context
- Randomness quality evaluation
- True random number generators (TRNGs)
- OCHRE circuits
- Conclusion, future prospects, references



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The “Random Group” at CAIRN–IRISA

Researchers:

- Prof. Olivier Senteys (ENSSAT–Univ. Rennes–INRIA)
- Dr. Arnaud Tisserand (CNRS)

PhD student:

- Dr. Renaud Santoro (2006–2009)

Engineers:

- Thomas Anger (2009–2010)
- Arnaud Carer (CAIRN)
- Philippe Quémerais (ENSSAT–Univ. Rennes)

Master student:

- Mohamed Habibi (2011)

Some Applications of Random Numbers

- **Lotteries, games and gambling**
- **Cryptography and security:**
key generation, initialization vectors, padding, nonces, stream ciphers, masking, blinding, randomization, ...
- **Probabilistic / randomized algorithms:**
Monte Carlo simulations, Las Vegas algorithms, ...
- **VLSI testing:**
random patterns, random schedules, ...
- **Digital communications:**
channel estimation/modeling, simulation, ...

Random Numbers: “Definition”

Simple definition (B. Schneier):

The output:

- looks random
- is unpredictable
- cannot be reproduced (for TRNGs)

Standard definition (e.g. see D. Knuth [4, chap. 3]):

The sequence of numbers $(x_1, x_2, x_3, \dots, x_{n-1}, x_n)$, with $\forall i, x_i \in S$, is **random** when the n numbers are:

- statistically independent
- uniformly distributed (*equally probable*)
- unpredictable

Chapter 3, *Random Numbers*, from [4] D. E. Knuth. *Seminumerical Algorithms*, volume 2 of *The Art of Computer Programming*. Addison-Wesley, 3rd edition, 1997

Randomness Quality Evaluation is Required

Extract from [8] (1988):

“Many generators have been written, most of them have demonstrably non-random characteristics, and some are embarrassingly bad.”

Randomness quality evaluation required at :

- **design time** (ensures minimal randomness for ideal environment)
- **run time** (check environment modifications, attacks)

Randomness quality evaluation methods:

- mathematical and physical **models**
- statistical **tests**

[8] S. K. Park and K. W. Miller. Random number generators: Good ones are hard to find. *Communications of the ACM*, 31(10):1192–1201, October 1988

Statistical Tests for Randomness Evaluation

- **FIPS 140-1** (1994): Security Requirements for Cryptographic Modules, *4 basic tests* (removed in 140-2 version, 2001/2002)
- **AIS 31** (2001+): Functionality Classes and Evaluation Methodology for Physical Random Number Generators. *Specific tests for TRNGs*
- **NIST 800-22** (2008+): A Statistical Test Suite for Random and Pseudorandom Number Generators for Cryptographic Applications.
More complete test suite
- **DIEHARD** (1995): by G. Marsaglia,
<http://www.stat.fsu.edu/pub/diehard/>
- **DIEHARDER** (2003+): *very complete test suite*, maintained by R. Brown,
<http://www.phy.duke.edu/~rgb/General/dieharder.php>
- **TestU01**: C library from P. L'Ecuyer and R. Simard [6] (2007+)
- **Universal test** from U. Maurer [7] (1992)
- ...

FIPS 140-1 Statistical Tests

Input: sequence S of 20000 bits (from the RNG)

Output: **PASS** or **FAIL**

- Monobit: **check that** $9654 < \#1(S) < 10346$
- Poker: split S into 5000 4-bit blocs, $\#B_i(S)$ number of blocs equal to i ($(0000)_2, (0001)_2, \dots, (1111)_2$), with $0 \leq i \leq 15$, **check that**

$$\chi^2_{15} : 1.03 < \left(\frac{16}{5000} \times \sum_{i=0}^{15} \#B_i(S)^2 - 5000 \right) < 57.4$$

- Run: **check that** $\#run(k, S) \in I_k$ for $1 \leq k \leq 6$ and

k	1	2	3	4	5	6+
I_k	[2267, 2733]	[1079, 1421]	[502, 748]	[223, 402]	[90, 223]	[90, 223]

- Long run: **check that** $\forall k \geq 34, \#run(k, S) = 0$

Notation: $run(k, S)$ = string of k consecutive 0s/1s (i.e. $1\underset{k}{\underbrace{0\dots 0}}1$ or $0\underset{k}{\underbrace{1\dots 1}}0$)

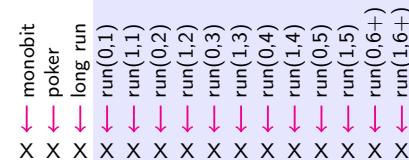
Statistical Tests Examples and Limitations

FIPS 140-1 tests

20kb sequences

Results format →

X = P or F



(*) some bad values for x_0

Types of Random Number Generators

Pseudo random number generator (PRNG):

- deterministic algorithms
- very high throughput and good statistical properties
- various algorithms → quality/throughput/cost tradeoffs

True random number generator (TRNG):

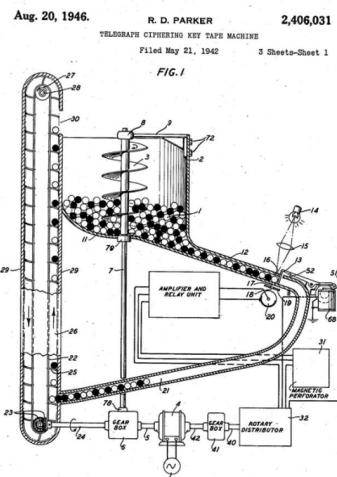
THIS WORK

- non-deterministic algorithms (physical random source)
- limited throughput
- quality = $func(\text{environment parameters}, \dots)$ → attacks

Hybrid random number generator (HRNG):

- HRNG = TRNG + PRNG
- very high speed and very good quality
- selection needs more research

Historical Hardware TRNGs



ATT Patent 1946, source: P. Kohlbrenner

TRNGs Selection

Physical noise source:

- quantum physics
- radioactive decay
- atmospheric noise
- thermal/Johnson noise
- jitter in ring oscillator sampling
- meta-stability
- noises in circuits: 1/f, shot, popcorn, crosstalk, ...
- ...

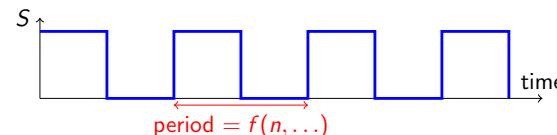
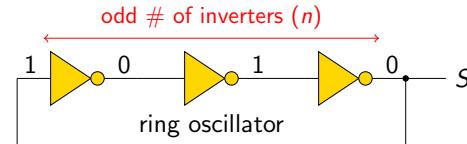
Characteristics:

- throughput (? Mb/s)
- randomness quality (bias, entropy/bit, stability, effects of environment variations, ...)
- security → fully integrated in the chip
- cost (silicon area, power consumption)

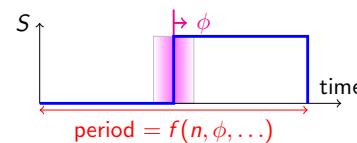
Free Running Ring Oscillator

inverter:

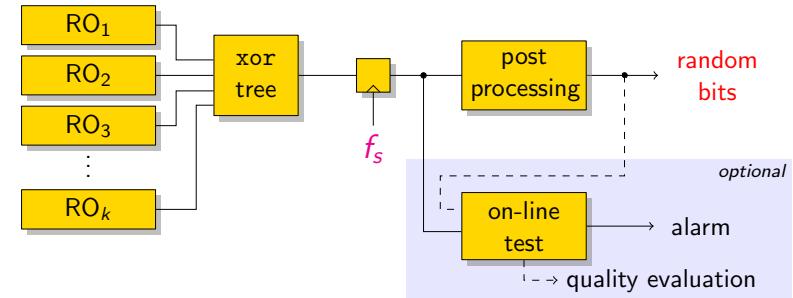
in	out
0	1
1	0



ϕ random jitter
(timing/phase instability)



Example of Ring Oscillator (RO) Based TRNG



Description:

- k free running ring oscillators
- f_s is the sampling frequency
- post processing: enhance statistical parameters
- on-line quality test (environment variations, attacks, ...)

Post Processing

Purpose: enhance statistical parameters of the output sequence

- reduce bias $Pr(x = 1) = 0.5 + \epsilon$ (AIS 31: $\epsilon < 0.0173$)
- increase entropy per bit (the real randomness)

Typical post processing methods:

- Von Neumann correction

input bits	(0,0)	(0,1)	(1,0)	(1,1)
output bit	none	1	0	none

- Linear feedback shift register (LFSR)
- Hash function (e.g. SHA)
- Ciphering (e.g. AES)
- Resilient function (e.g. error code computations)
- ...

Trade-off: entropy per bit, data rate, cost, quality

RO Based TRNG Example

[14] B. Sunar, W. J. Martin, and D. R. Stinson. A provably secure true random number generator with built-in tolerance to active attacks. *IEEE Transactions on Computers*, 56(1):109–119, January 2007

Description:

- $k = 114$ RO of 13 inverters
- resilient function: BCH(256, 13, 113) code
- mathematical model (but not realistic assumptions)
- data rate 2.5 Mb/s on FPGA

Problems:

- very complex calibration (external measurement of the jitter!!!)
- too many transitions in the xor tree
- setup/hold violations in the flip-flop
- ...

Other TRNG References

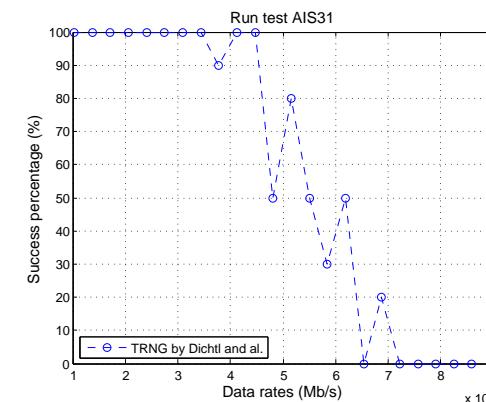
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- [2] M. Dichtl and J. D. Golic. High-speed true random number generation with logic gates only. In *Proc. Cryptographic Hardware and Embedded Systems (CHES)*, volume 4727 of *LNCS*, pages 45–62. Springer, September 2007
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- [1] J.-L. Danger, S. Guille, and P. Hoogvorst. High speed true random number generator based on open loop structures in FPGAs. *Microelectronics Journal*, 40(11):1650–1656, November 2009

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Example of Measurements on FPGAs

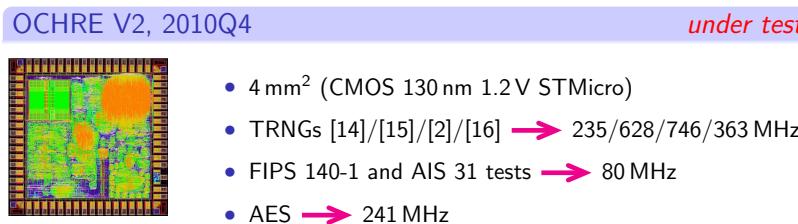
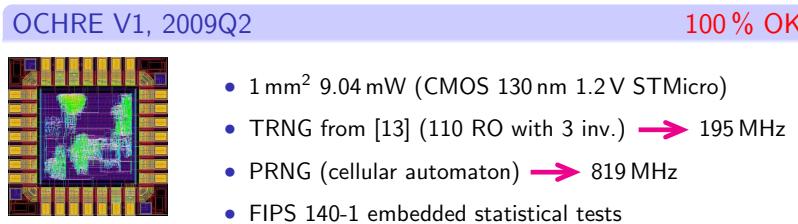
TRNG from [2] (Altera Stratix II):



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OCHRE Circuits (On-Chip Randomness Extraction)

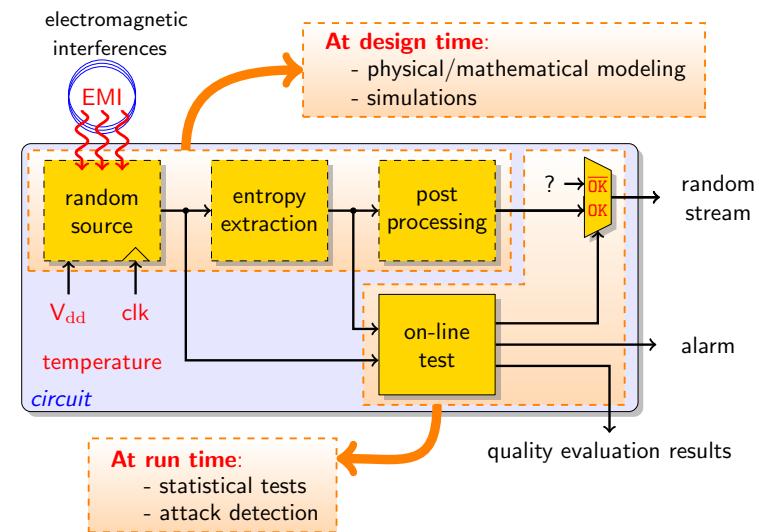


We also have **FPGA** implementations (Xilinx, Altera and Actel).

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TRNG Design and Use



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Conclusion & Future Prospects

- TRNGs are important elements of security systems
- Randomness quality evaluation is **very complex**
→ accurate modeling, simulations, measurements, ...
- Embedded security systems → on-line quality evaluation
- We have implementations for both **ASIC** and **FPGA** targets
- Currently: **very intensive measurements**
Environment parameters: V_{dd} , temperature, electromagnetic radiations, clock variations, ...

Future research topics:

- Hybrid generators = TRNG + PRNG
- Design space exploration at system level

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The end, some questions ?

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Thank you