Impact of the Flicker Noise on the Ring Oscillator-based TRNGs

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Outline

Introduction

- True Random Number Generators (TRNG): the basic building block of most cryptographic system
- Also used in :
  - Simulation
  - AI
  - Gambling
- Contrary to DRNG (Deterministic), they use a real physical noise source
- Principles:
  - Jitter – ring oscillators, PLL, STR – this presentation
  - Metastability
  - Chaos

How random is random?

Example 1 : Which is more random?

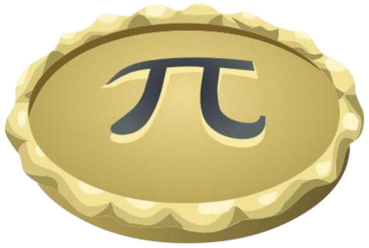
1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

Equiprobable

Intuitively, streaks are not random, but 50,6% of 20 random bits have streaks of ≥5

Example 2 : Is this random?

0 0 1 0 0 1 0 0 0 0 1 1 1 1 1 1 0 1 1 0 1 0



Random, but can be guessed with the right knowledge

Proving randomness

- Looking at generated random numbers does not fully guarantee randomness
- Statistical tests have a non-zero probability of suffering from type I ot type II errors (false positive or false negative)
- Standards (AIS 20/31) require a stochastic model to prove randomness

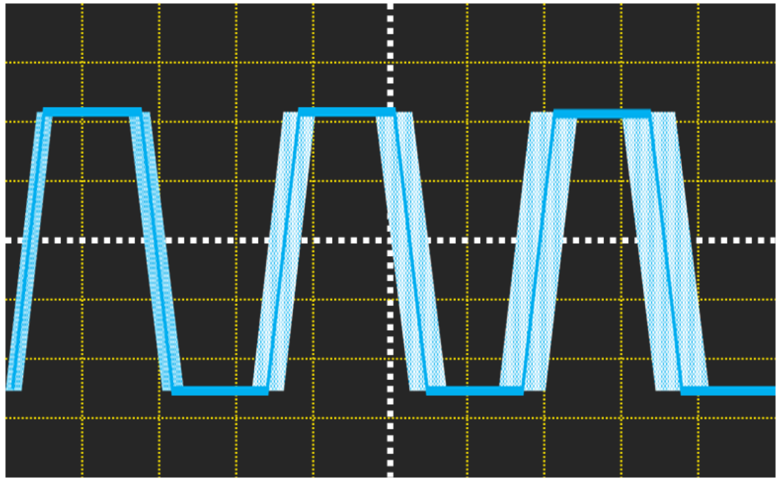
Use of noise models (phase noise)

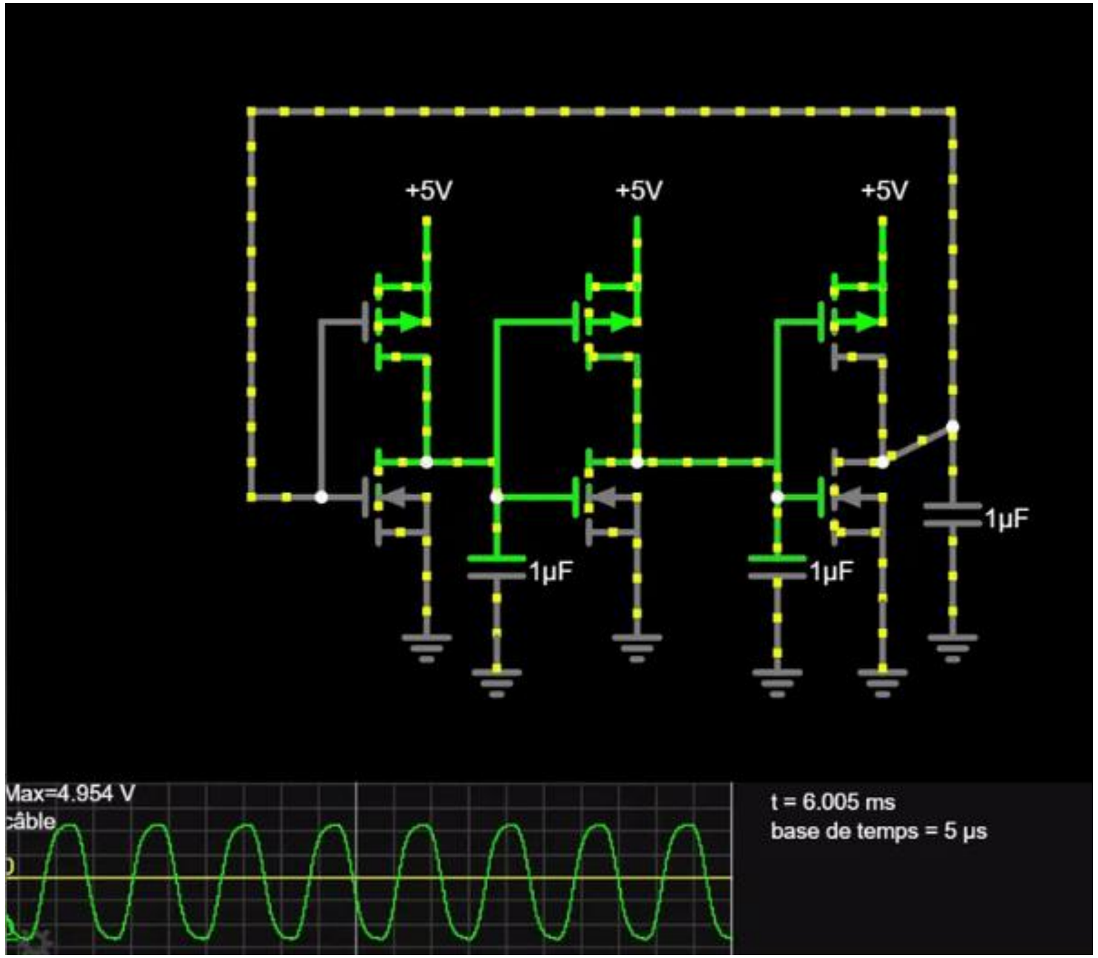
Identification of the physical phenomena causing entropy → Generate a stochastic model (TRNG)

2. Noise sources and TRNG structures

Ring oscillator description

- Structure: odd number of inverters
- The periodical signal is not perfect - jitter
- Jitter increases with accumulation time





Physical noise sources

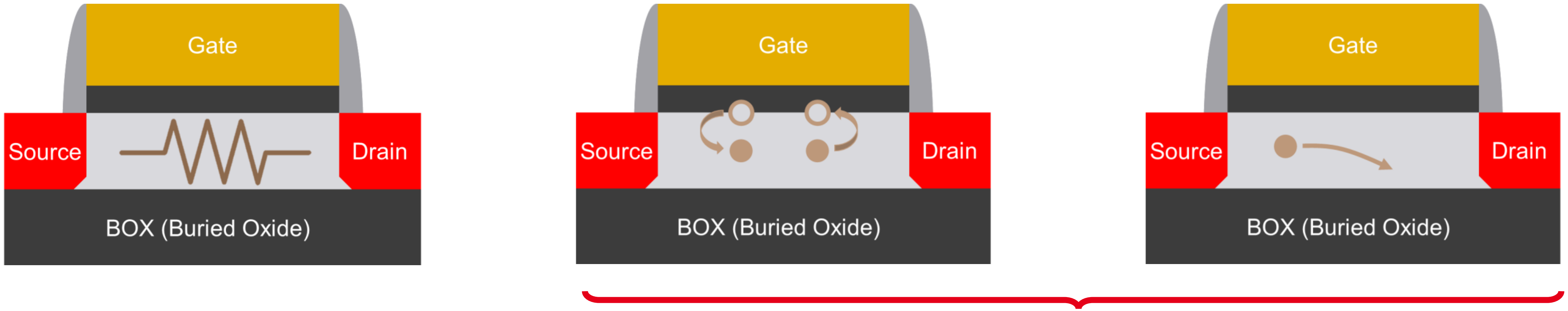
Thermal noise

[Nyquist 1928]

Flicker noise

Carrier Number Fluctuation (CNF)
[McWorther 1957]

Carrier mobility flucturations (CMF)
[Hooge 1969]



Random, not correlated

Random, correlated

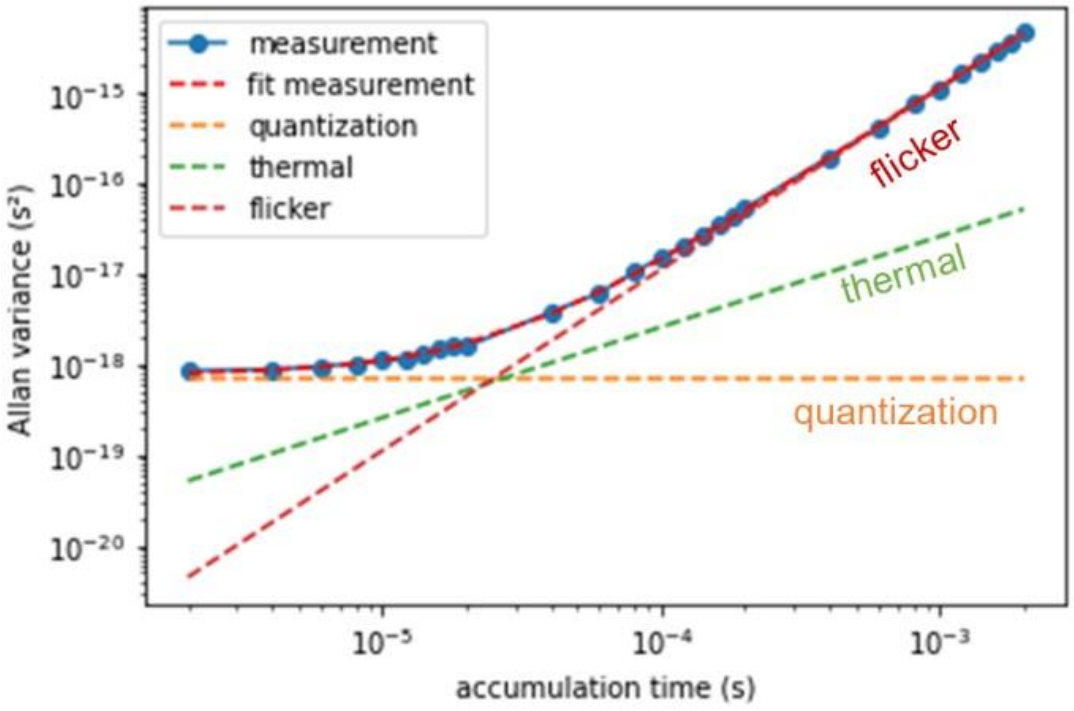
For TRNGs : autocorrelation = predictability

Sources of jitter (non-exhaustive)

- Global
- Deterministic
- Parasitic

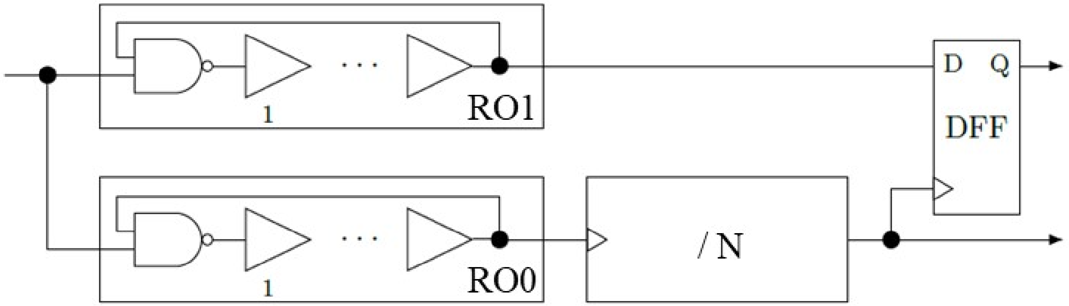
reduced by the differential principle

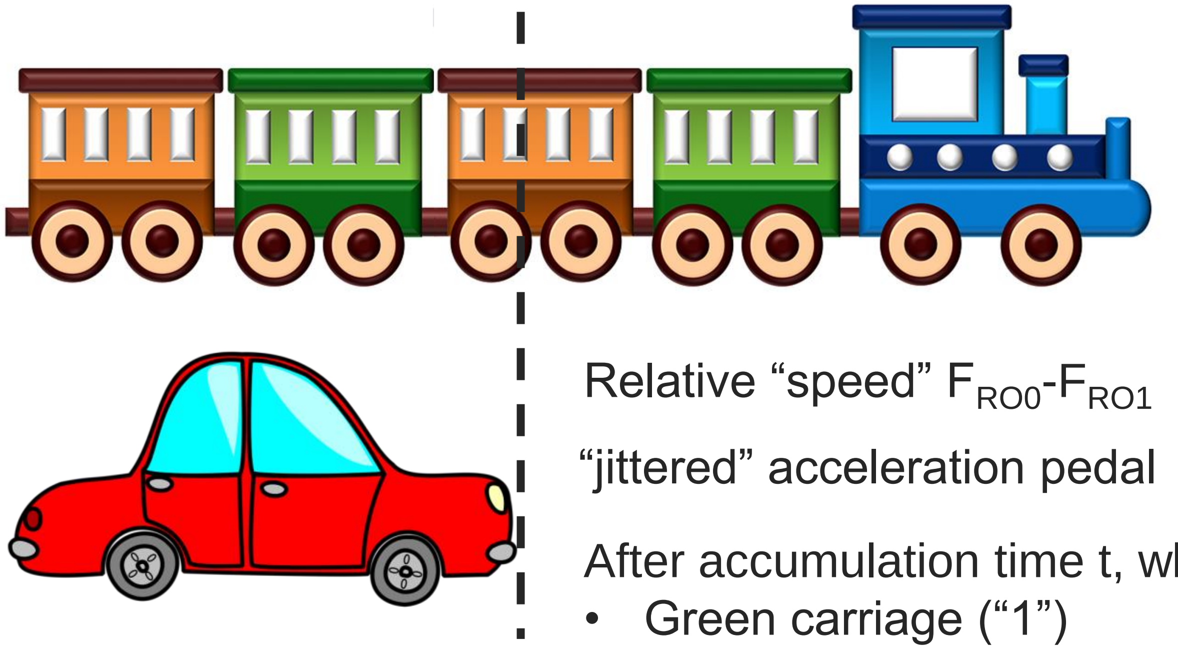
- Cross-talk → isolation
- Measurement
  - Quantization
- Physical
  - Thermal
  - Flicker



Use of jitter in TRNGs

- Elementary RO TRNG:
  - RO0 as a reference clock generator
  - RO1 as an entropy source





Relative “speed” F_{RO0}-F_{RO1}

“jittered” acceleration pedal

After accumulation time t, what is the position of the car?

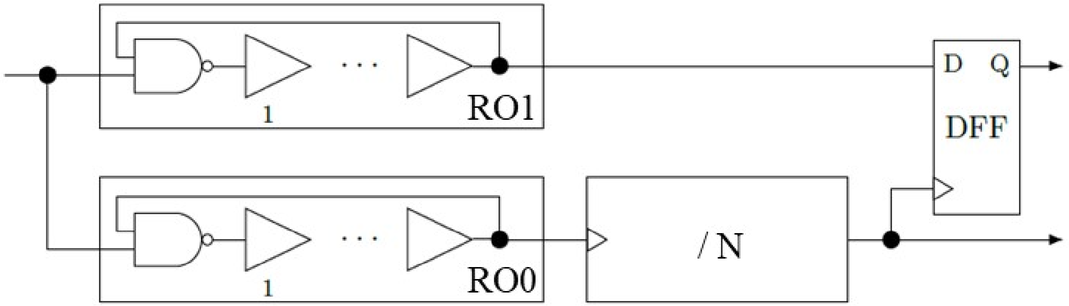
- Green carriage (“1”)
- Brown carriage (“0”)

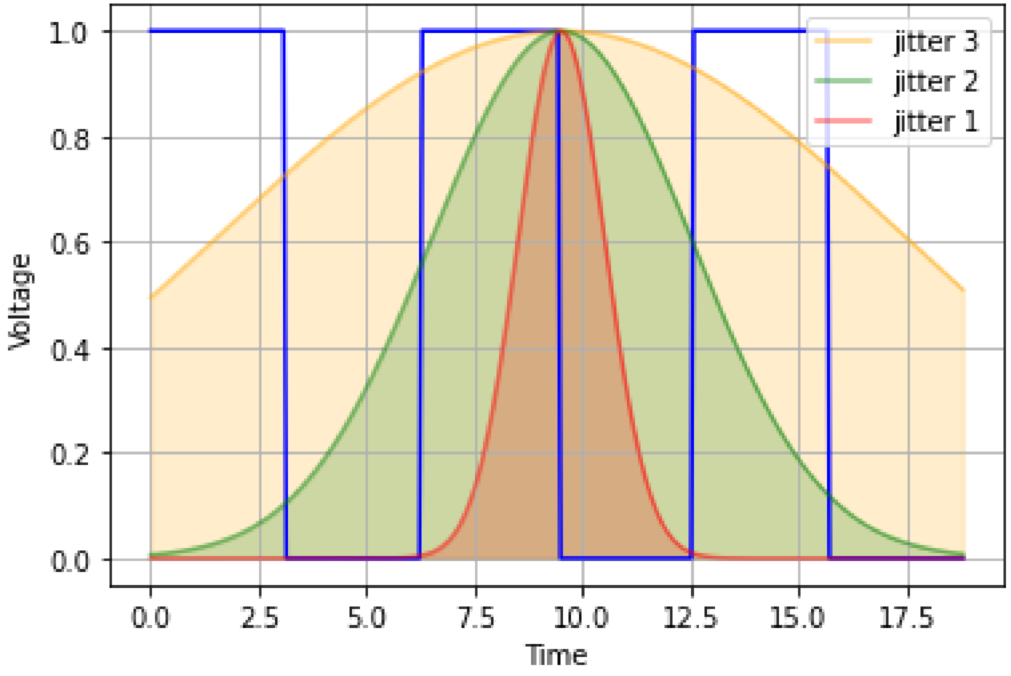
Use of jitter in TRNGs

- Elementary RO TRNG:
  - RO0 as a reference clock generator
  - RO1 as an entropy source

- Principle of jitter transfer – referential change
  - 1 perfect RO signal (clk1)
  - 1 jittered RO signal (clk0)

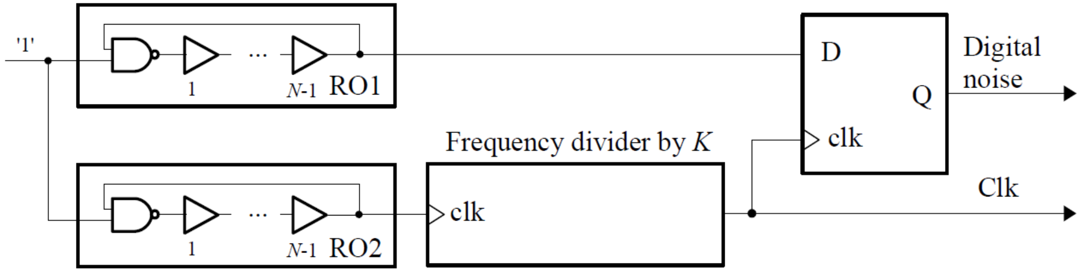
- Frequency divider: accumulated jitter is large enough for the entropy requirements





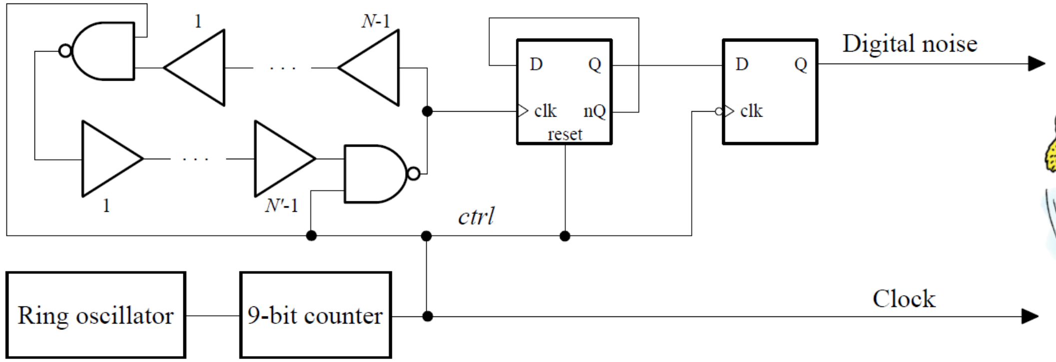
Other types de RO-TRNG

1. Elementary RO-TRNG



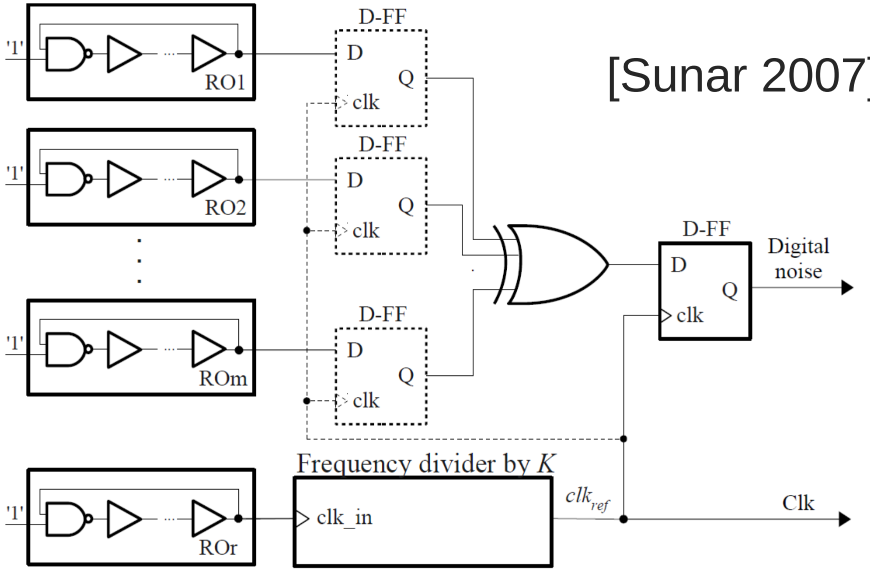
[Baudet 2011]

2. Transient Effect RO-TRNG

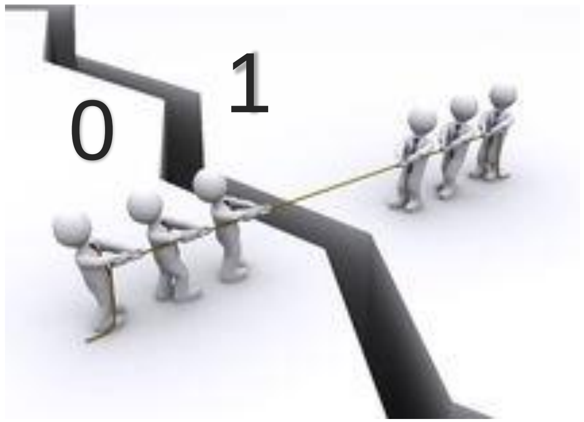


[Haddad 2015]

3. Multi-RO-TRNG



[Sunar 2007]

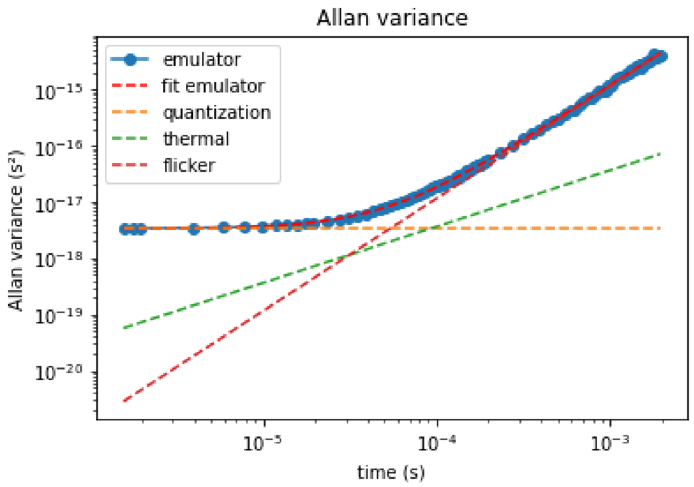


Current entropy models

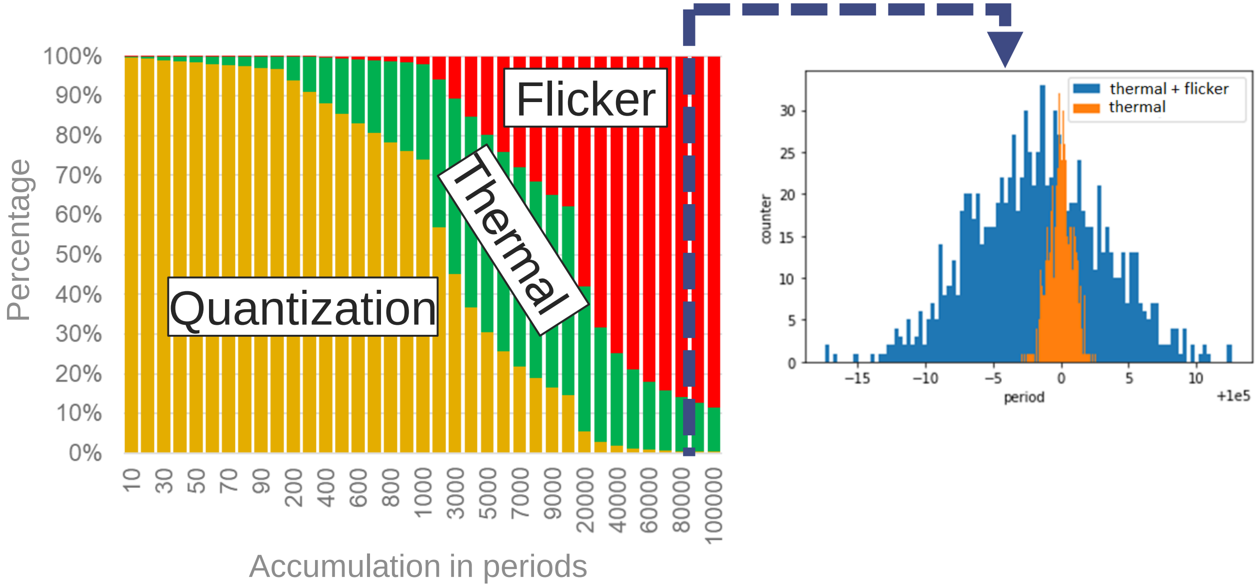
1. Isolate and use only the thermal jitter component
2. Postulate that only the thermal noise contributes to the entropy rate of the TRNG

Issues:

1. How can one be sure that thermal noise is well determined? (hidden by quantization)



2. TRNG working point is in a flicker dominated region. Influence on entropy?



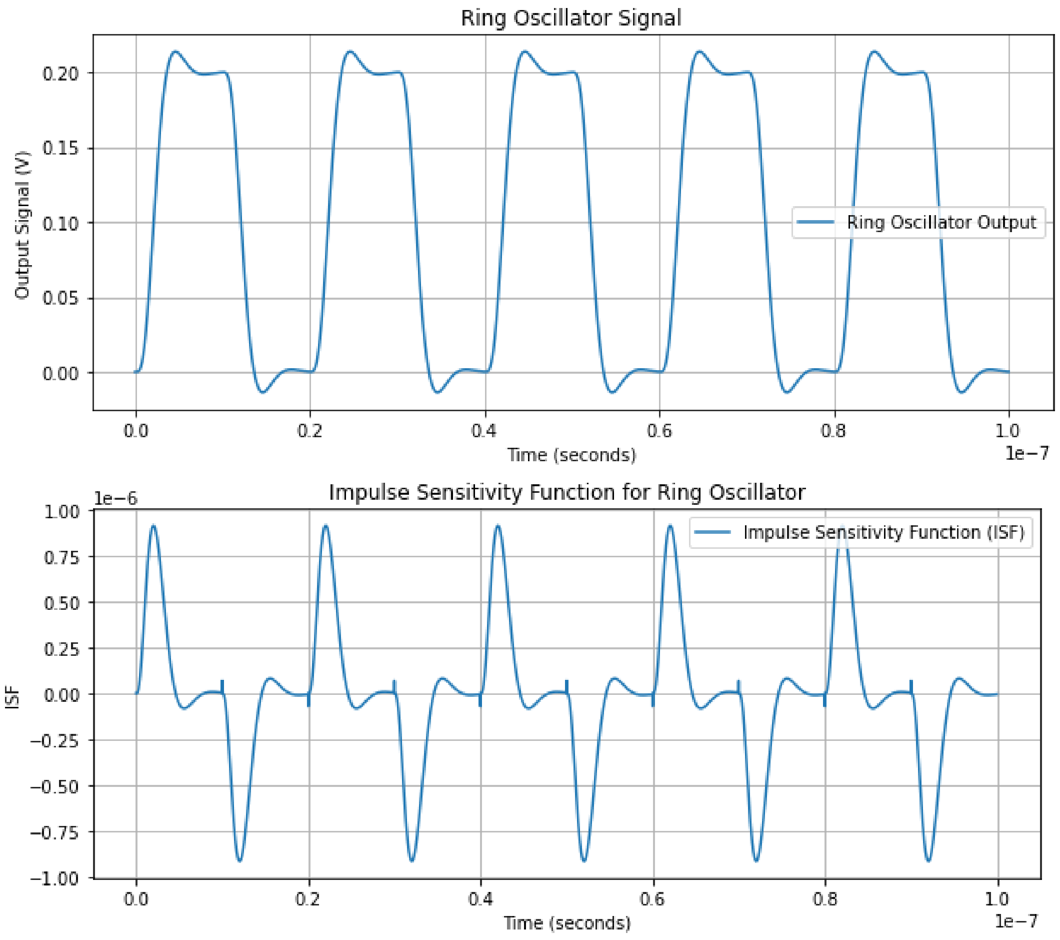
Solution : Emulator

3. Emulator

Motivation and principle

- Motivation:
  - We need to modify the amplitudes / to cancel noise sources on demand
  - Conventional simulation tools may take ~week to simulate 1M periods of a RO
- Use of the [Hajimiri 1999] model :
  - There is an impact of the noise on phase noise only during transient phases
  - Susceptibility of a signal to be influences in terms of phase noise (Impulse Sensitivity Function)
- Absolute phase :

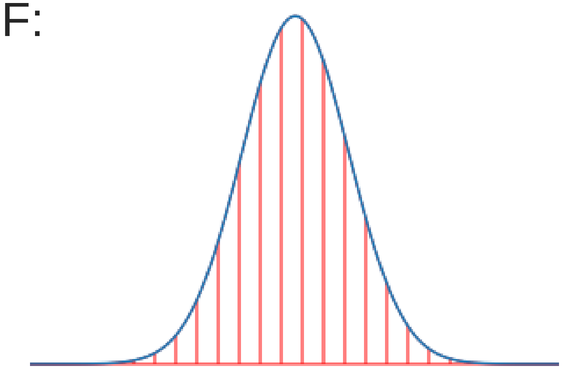
$$\phi(t) = \int_{-\infty}^{t} \frac{\Gamma(\omega_0 \tau)}{q_{max}} \cdot i(\tau) \cdot d\tau$$



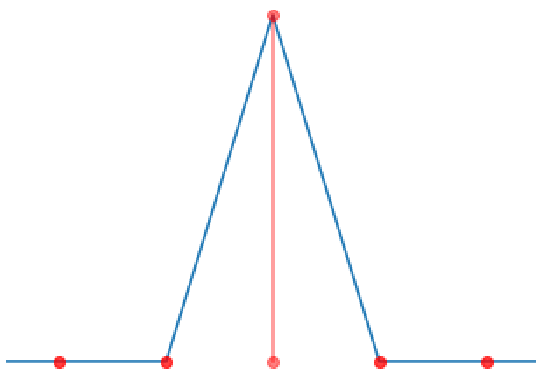
*schematic

Hypothesis for emulator

- Simplification : TRNGs only need the trigger moments of rising (/falling) edges
- ISF:



$\Rightarrow$



$\Leftrightarrow$

reduction

$$\frac{\Gamma(\omega_0\tau)}{q_{max}} \cdot i(\tau) \ = \ A \cdot \delta i$$

$A \ - all\ encompasing\ amplitude\ term$

$\delta i \ - generic$ "unitary" $noise\ term$

- Time deviation :

$i_{th}(\tau)$ - thermal

$i_{fl}(\tau)$ - flicker

$$\frac{2\pi}{\omega} \cdot \phi(t) = \frac{2\pi}{\omega} \cdot \int \frac{\Gamma(\omega_0\tau)}{q_{max}} \cdot i(\tau) \cdot d\tau \xrightarrow{assembling} \frac{2\pi}{\omega} \cdot d\phi(t_i) = A_{th} \cdot \delta i_{th}(t_i) + A_{fl} \cdot \delta i_{fl}(t_i)$$

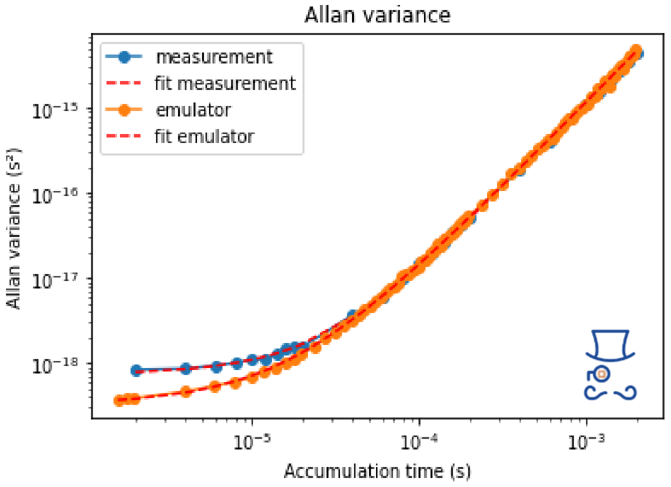
- Each period of the RO : $\mathrm{d}t_i = T_0 + A_{th} \cdot \delta i_{th}(t_i) + A_{fl} \cdot \delta i_{fl}(t_i)$
- Rising edges : $t_i = i \cdot T_0 + \sum_{-\infty}^{t_i} \left(A_{th} \cdot \delta i_{th}(t_i) + A_{fl} \cdot \delta i_{fl}(t_i)\right)$

A_{th}, A_{fl} are amplitudes $\rightarrow$ to be calibrated
$\delta i_{th}, \delta i_{fl}$ are generic terms for thermal and flicker noises (Python colorednoise)

Validation

ASIC (28nm FD-SOI, 101 elements, 500MHz)

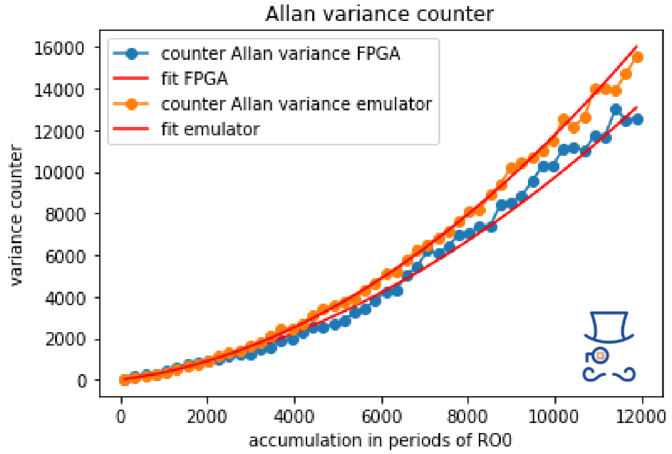
$$dt_i^{RO} = T_0 + \sqrt{\frac{a_1 \cdot T_0}{factor_{th}}} \cdot \delta i_{th}^{RO} + \sqrt{\frac{a_2 \cdot T_0^{\,2}}{factor_{fl}}} \cdot \delta i_{fl}^{RO}$$



	a_2 (flicker)	a_1 (thermal)	a_0 (quantization)
Measurement	$1{,}11 \cdot 10^{-9}$	$2{,}56 \cdot 10^{-14}$	$7{,}37 \cdot 10^{-19}$
Emulator	$1{,}16 \cdot 10^{-9}$	$2{,}81 \cdot 10^{-14}$	$3{,}23 \cdot 10^{-19}$
Error (%)	4,75%	9,75%	56,21%

FPGA(ARTY A7)

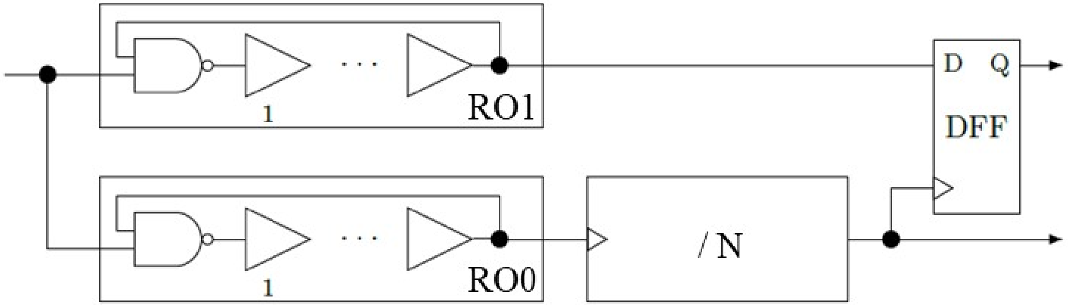
$$dN_i = N + \sqrt{\frac{a_1 \cdot N}{factor_{th}}} \cdot \delta i_{th}^{RO} + \sqrt{\frac{a_2 \cdot N^2}{factor_{fl}}} \cdot \delta i_{fl}^{RO}$$



	a_2 (flicker)	a_1 (thermal)	a_0 (quantization)
Measurement	$6{,}90 \cdot 10^{-5}$	$2{,}81 \cdot 10^{-1}$	$1{,}15 \cdot 10^{1}$
Emulator	$9{,}13 \cdot 10^{-5}$	$2{,}62 \cdot 10^{-1}$	$9{,}51 \cdot 10^{1}$
Error (%)	32,3%	6,72%	91,8%

Emulating an Elementary RO TRNG

- Hypothesis:
  - We “transfer” all phase noise into one of the ROs
- $$\begin{cases} dt_i{}^{RO1} = T_0{}^{RO1} \\ dt_i{}^{RO0} = T_0{}^{RO0} + A_{th} \cdot \delta i_{th}{}^{RO0} + A_{fl} \cdot \delta i_{fl}{}^{RO0} \end{cases}$$
- If duty cycle = 50%:



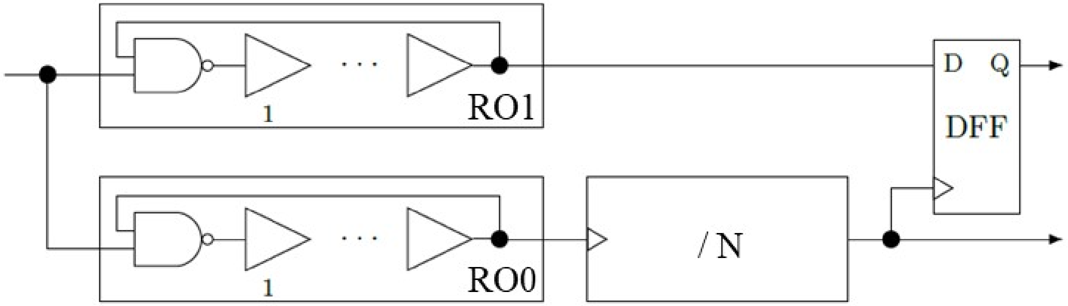
Output bit : $\left\lfloor \frac{absolute\ jitter\ of\ RO_0}{T_0{}^{RO1}}\ mod\ 1 + 0.5 \right\rfloor$

$$\left\lfloor \frac{\sum_{t_i}\left(N \cdot T_0{}^{RO0} + \sqrt{\frac{a_1 \cdot N \cdot T_0{}^{RO0}}{factor_{th}}} \cdot \delta i_{th}{}^{RO0}(t_i) + \sqrt{\frac{a_2 \cdot N^2 \cdot T_0{}^{RO0^2}}{factor_{fl}}} \cdot \delta i_{fl}{}^{RO0}(t_i)\right)}{T_0{}^{RO1}} mod 1 + 0.5 \right\rfloor$$

Emulating an Elementary RO TRNG (Python)

- Python script uses colorednoise library:
  - Based on [Timmer 1995]
  - For each frequency of the spectrum we generate random sequences whose amplitude is proportional to the desired spectrum

$$S(\omega) \sim (1/\omega)^{\beta}$$




```python
def ERO_bits(T1,T2,Ath,Afl,N,size):

    #generate noise
    di_thermique = cn.powerlaw_psd_gaussian(0 ,size)
    di_flicker = cn.powerlaw_psd_gaussian(1,size)

    dti_emulator=N*T2*np.ones(size)
           +di_thermique*np.sqrt(Ath*T2*N/factor_th)
           +di_flicker*np.sqrt(Afl*((N*T2)**2)/factor_fl)

    ti_emulator=np.cumsum(dti_emulator)
    bits=np.round((ti_emulator/T1)%1)
```

Script can be found at:

Free

OpenTRNG

https://opentrng.org/

https://github.com/opentrng/papers/tree/master/ches2024

4. Consequences of noise (flicker) on random number generation

Autocorrelation of bits

- Autocorrelation represents the predictibility introduced by flicker noise

$$\rho_k = \sum_i \frac{(X_{i+k} - E(X_{i+k}))(X_i - E(X_i))}{\sigma_{X_{i+k}} \cdot \sigma_{X_i}}$$

- Variation of flicker noise amplitude of the time series:

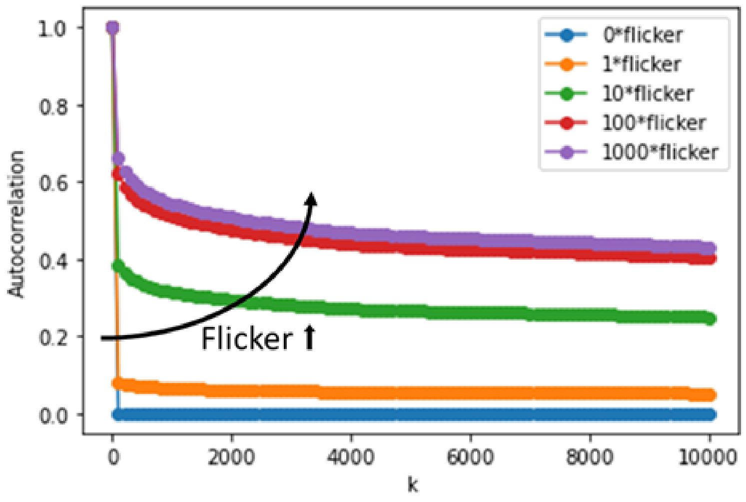
$$dt_i{}^{RO} = N \cdot T_0 + \sqrt{\frac{a_1 \cdot N \cdot T_0}{factor_{th}}} \cdot \delta i_{th}{}^{RO} + \sqrt{\frac{M \cdot a_2 \cdot (N \cdot T_0)^2}{factor_{fl}}} \cdot \delta i_{fl}{}^{RO}$$

- Bit series:

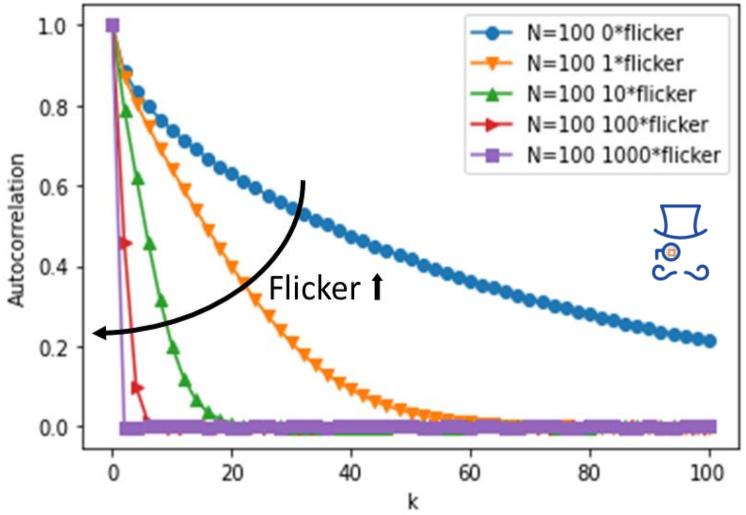
$$\left\lfloor \frac{t_i{}^{RO0}}{T_0{}^{RO1}} mod1 + 0.5 \right\rfloor$$

- Sampling might reduce the autocorrelation effect introduced by flicker noise

Raw time series

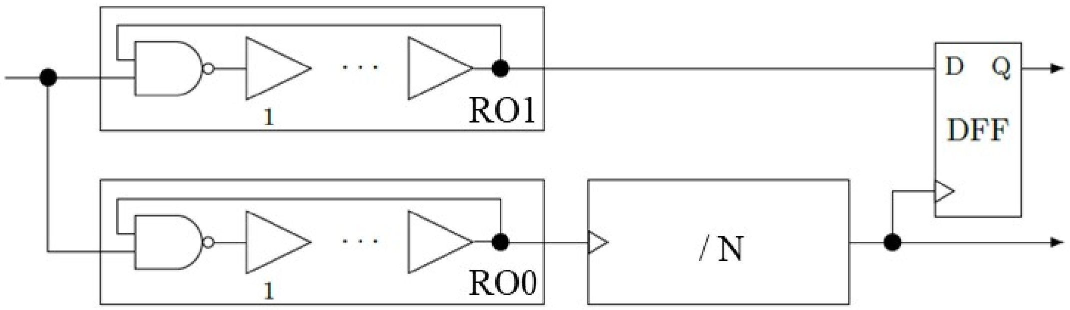


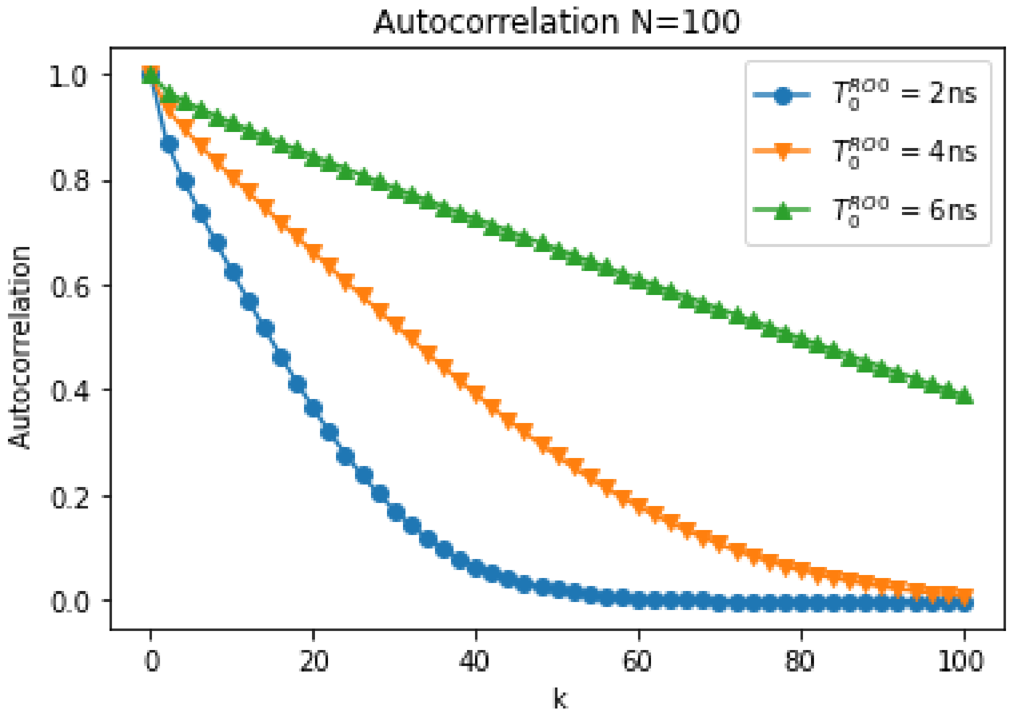
Bits of the ERO-TRNG



Influence of sampling on autocorrelation

- Assumption: « The sampling limits the autocorrelation introduced by flicker noise »
- If sampling with RO0 limits the depth of the autocorrelation ⇒ by changing the period of RO0, the depth of autocorrelation increases
- Conclusion: The sampling limits autocorrelation by a lower bound of the frequency

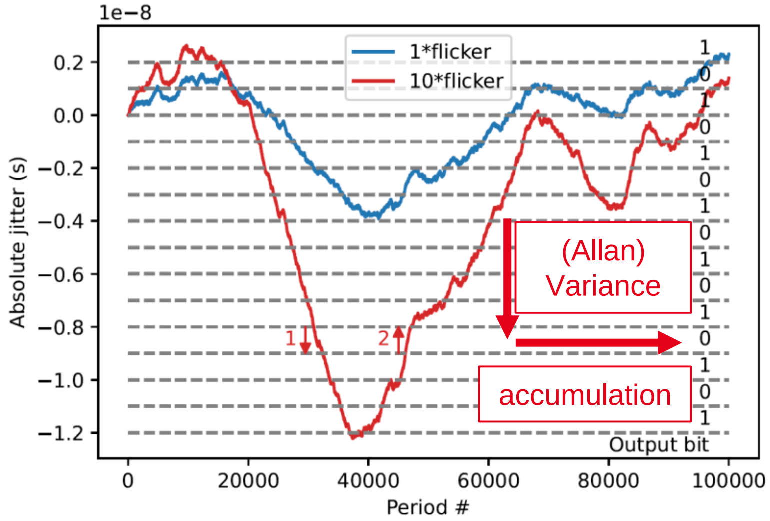


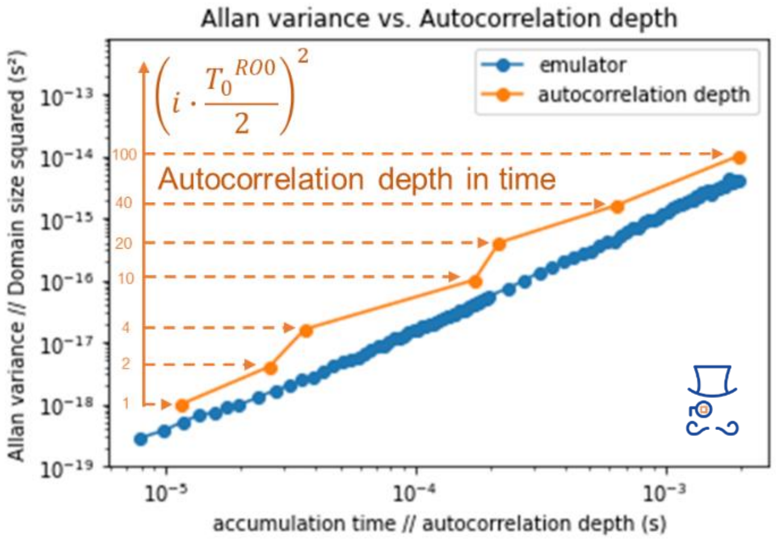


Depth of the autocorrelation

- Phase perspective : determination of the output bit
- Bit perspective: a transition (from “0” to “1”) does not allow to determine if it is the result of an increase or decrease in absolute jitter
  - For each transition ⇒ reset of the perceived phase and removal of the memory effect
- The deviation of half a “domain” → mean deviation is given by the (Allan) variance
- The depth of the autocorrelation is given by the accumulation time necessary for the Allan variance to reach half the period of the sampling RO

$$a_2 \cdot t^2 + a_1 \cdot t = \left(\frac{T_0^{RO0}}{2}\right)^2 \Rightarrow t = \frac{-a_1 + \sqrt{{a_1}^2 - 2 \cdot a_2 \cdot {T_0^{RO0}}^2}}{2a_2}$$





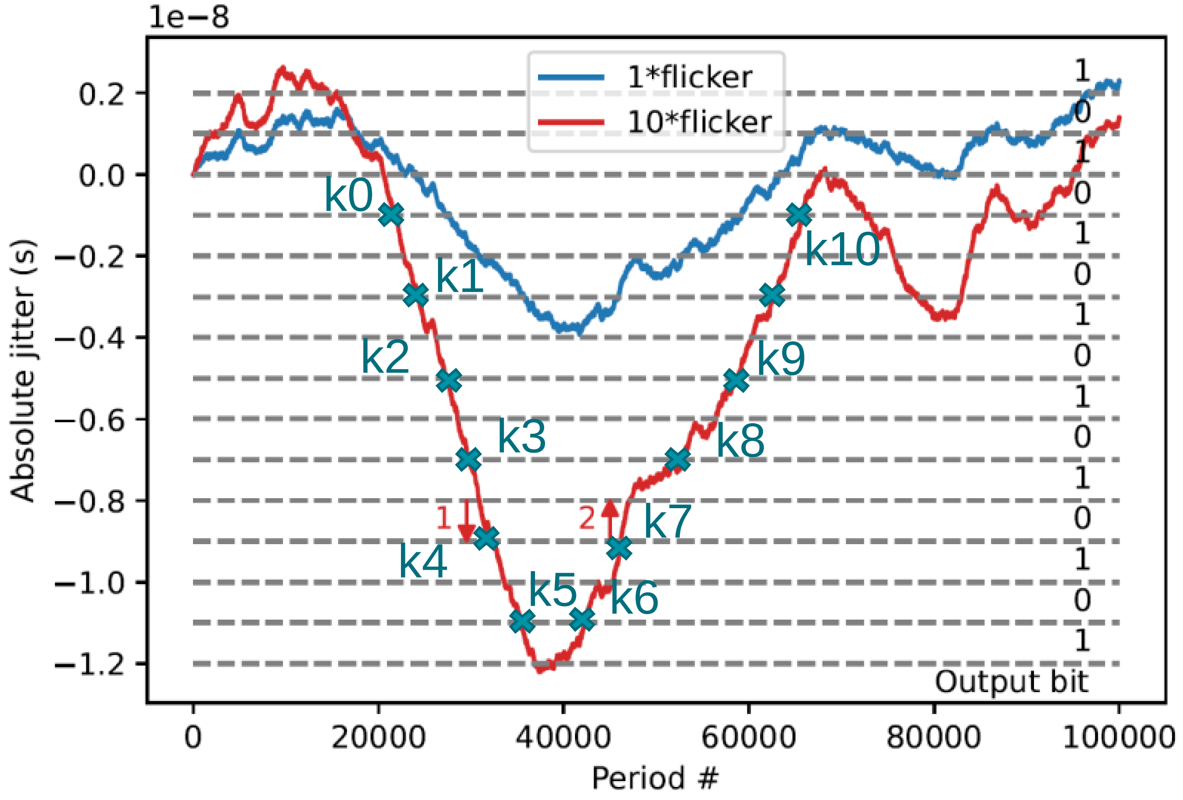
Jitter – bit relationship

- Absolute jitter:

$$\frac{2\pi}{\omega}\cdot\phi(t) = \frac{2\pi}{\omega}\cdot\int\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau\ \ (divergent)$$

- Output bit of ERO-TRNG (same T_0):

$$bit(t) = \left\lfloor \frac{\int_{-\infty}^{t}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau}{2\omega_0 T_0}\ mod\ 1 + 0.5\right\rfloor$$



$$bit(t) = \left\lfloor \frac{\int_{t_0}^{t_1}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau + \int_{t_1}^{t_2}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau + \cdots + \int_{t_{k-1}}^{t_k}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau + \int_{t_k}^{t}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau}{2\omega_0 T_0}\ mod\ 1 + 0.5\right\rfloor$$

$$\frac{T_0}{T_0}\ mod\ 1 = 0$$

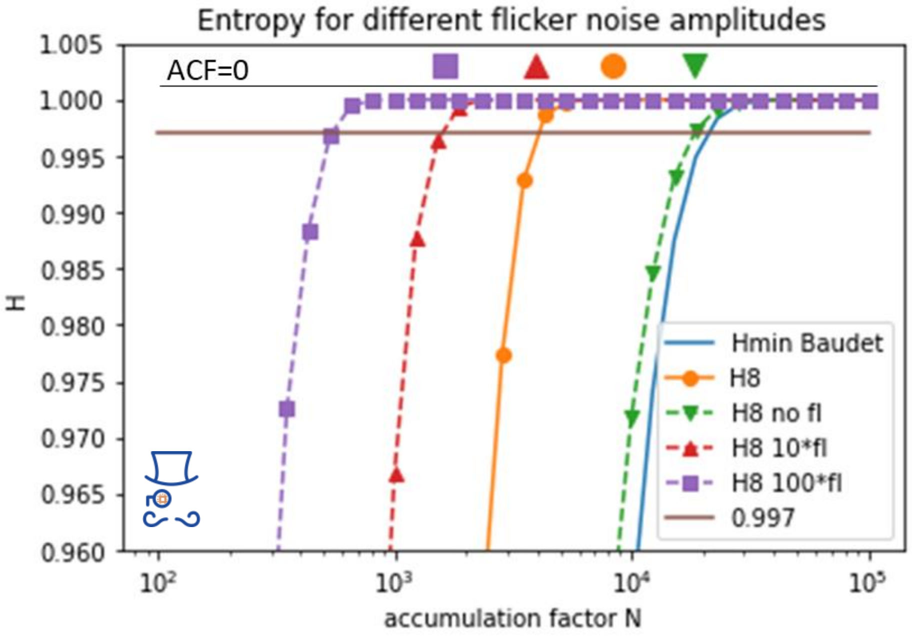
1: modulo function reinitialises phase

$$bit(t) = \left\lfloor \frac{\int_{t_k}^{t}\frac{\Gamma(\omega_0\tau)}{q_{max}}\cdot i(\tau)\cdot d\tau}{2\omega_0 T_0}\ mod\ 1 + 0.5\right\rfloor$$

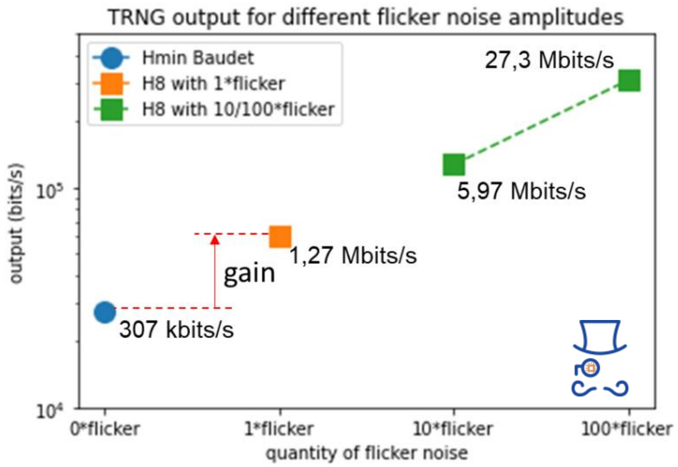
2: non-cancelled part remains in the same « domain »

The effect of the flicker noise on entropy

- Entropy rate calculated on 8 bits for different flicker noise amplitudes
- Orange curve : « standard » quantities of flicker/thermal noises
- Green curve with thermal component only fits [Baudet 2011] model
- Generally, flicker noise increases entropy



- Implications on output
  - For ACF = 0 and Entropy rate > 0.997 ⇒ 4x increase in the output for our device for “standard” noise quantities
  - Caution: those conditions are achieved at 99.98% flicker (i.e. 4x in output for 5000x flicker noise)



Conclusion

- Study of the influence of the flicker noise: emulator adapted to RO-TRNG applications
  - Tool: Simple emulator adapted to TRNG, Python-based
  - Advantage: Reproduction and/or modification of real parameters
- Influence of the flicker noise on the behaviour of the TRNG
  - Take away: From a bit perspective, autocorrelation doesn’t have any influence starting from the point where jitter is greater than the half-period
    - Flicker is not always harmful
    - Can improve the bit rate of the TRNG
    - Can simplify jitter characterization
    - Opens the perspective for a new stochastic model integrating it
  - What the paper does not provide: Entropy computation knowing previous bits or phases
- Perspectives
  - Emulator: study of other configurable conditions (drift, aging, duty cycle etc.) and other TRNG structures
  - Noise sources: development of a new stochastic model integrating noise sources adapted to advanced technological nodes (thermal, flicker, RTN, etc.)

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