An EMI Reduction Methodology Based on Nonlinear Dynamics

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University of Ferrara

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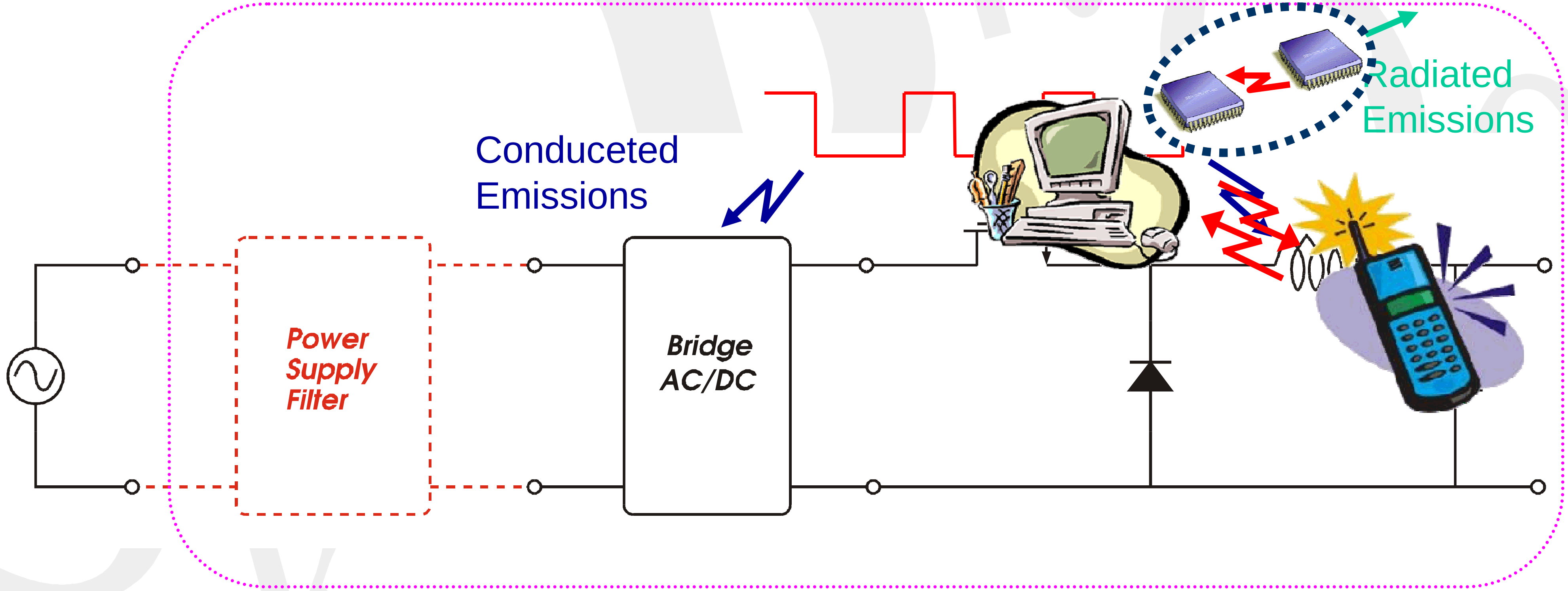
Outline

- EMI due to timing signals and “signal-processing” based reduction methods
- Clock signals
  - Sinusoidal FM
  - Cubic (patented) FM
  - Chaos Based FM
    - Analytical results (statistical approach)
- Numerical and experimental results
- PWM signals
  - Boost DC/DC converter prototype
- Fast FM and implementation of a low EMI clock generator
  - FM modulator based on a PLL
  - High Throughput RNG based on Chaotic Maps
  - SATA and SATA-II
- Conclusion

EMI due to timing signals

EMI Problem: coupling between *source* and *victim*

- **Source**: radio transmitter, power lines, electronic circuits,…
- **Victim**: radio receiver, electronic circuits and devices,…
- **Coupling methods**: conducted, inductively/capacitively coupled, radiated,…



Usual solution: reduce coupling by means of filters and shields (cables, connectors)

Problems: *Cost, No guarantees to solve EMI problem*

An "a priori" solution

In several applications filters and shields cannot be employed:

- μP and board clock signals
- Mixed-mode analog/digital ICs

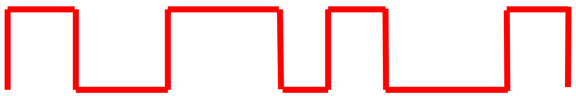
⇨ An *a-priori (design-time)* solution (on the EMI source) is required

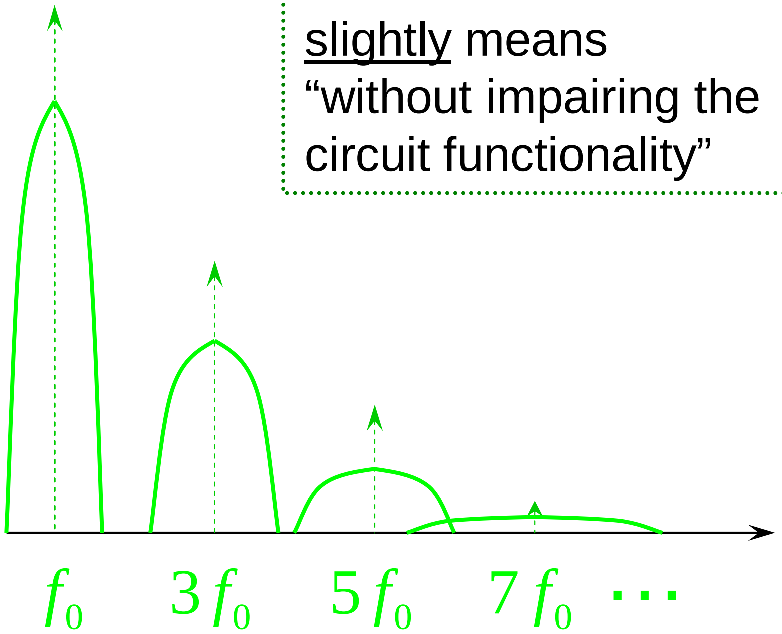
REMARKS

- Clock signals produce EMI at frequencies corresponding to harmonics
- Regulation standard set a limit on peak emissions (*mask*)

Basic Idea: introduce a suitable modulation to slightly perturb a normally narrowband signal

$\Longrightarrow$ energy spread over a larger bandwidth: peak value reduction



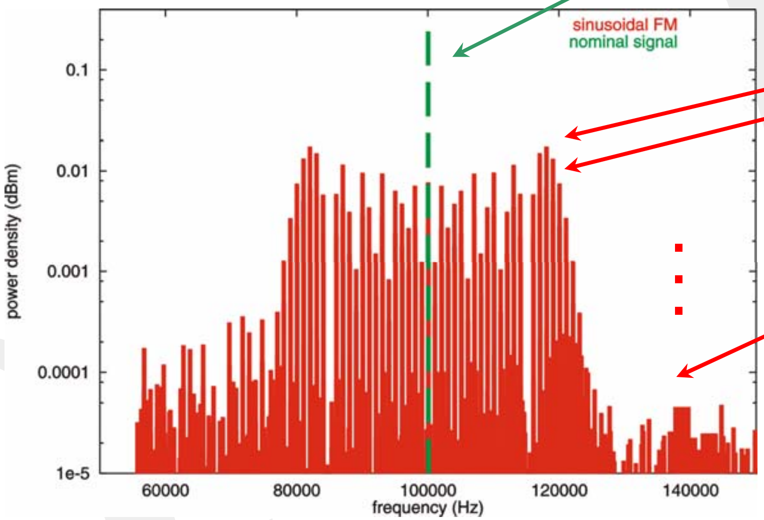


slightly means "without impairing the circuit functionality"

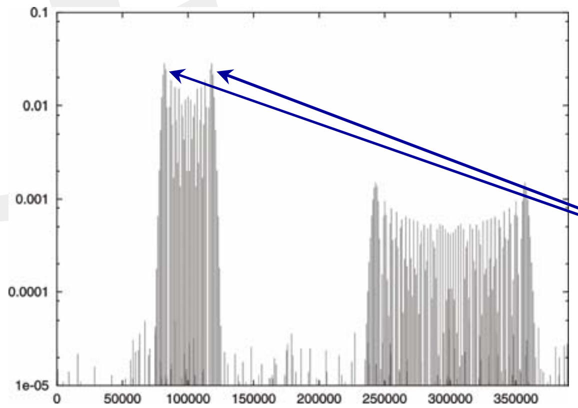
A first idea for the modulation

$s_c(t) = A\sin\left(2\pi f_0 t\right)$

$$s_{\mathrm{FM}}(t) = A\sin[2\pi f_0 t + m\sin(2\pi f_m t)] = A\sum_{k=-\infty}^{\infty} J_k(m)\cos[2\pi(f_0 + k f_m)t]$$



- Spectral component at frequencies $f_0 \pm k f_m$
  (Ex: f_0=100KHz, f_m=1Khz, m=20)
- Power of $s_{\mathrm{FM}}(t)$ = power of $s_c(t)$ and the bandwidth is $[f_0 - \Delta f(1+1/m), f_0 + \Delta f(1+1/m)]$
  ⇒reduction of the power spectrum peak



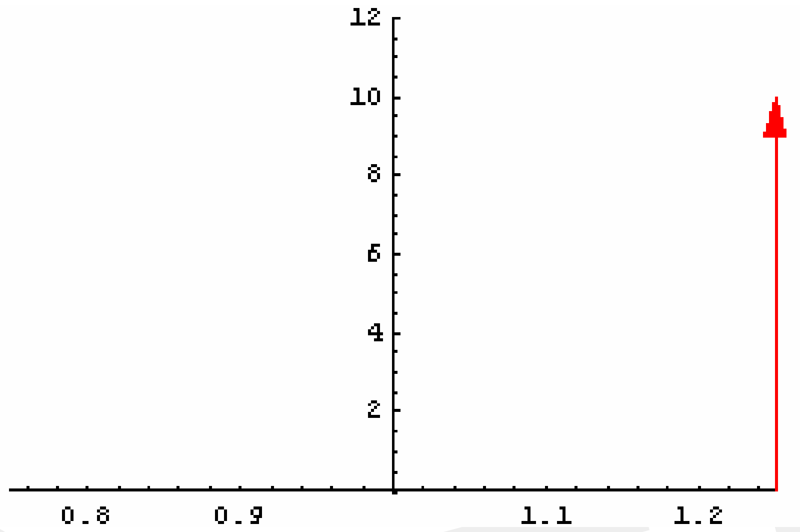
- Clock signal: same effect for each harmonic bandwidth $2\Delta f(n+1/m) \approx n(2\Delta f)$
- Successfully applied to get 10dB EMI reduction DC/DC converters (Lin, Chen *Trans. PE*, 1994)

Problem: FM sinusoidal modulation is not optimal for spectrum spreading

...and a better one - I

- $s_{FM}(t)$ instantaneous frequency $f(t) = f_0 + \Delta f \cos(2\pi f_m t)$

$\Longrightarrow$ for "quasi-stationary" modulation power concentrates where $ds_m(t)/dt$ is small

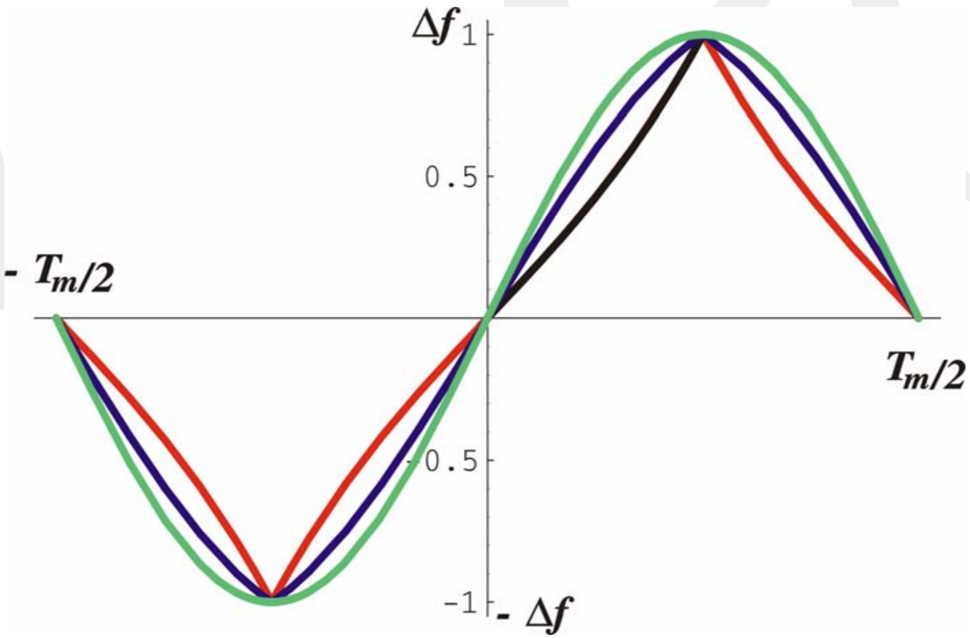


- Sin: peak in the spectrum if $s_m(t)$ min or max
  reduced amplitude corresponding
  to zero crossing $s_m(t)$ (large derivative)

- Hardin *et al* (Lexmark; US patent # 5,488,627, 1996) proposes to use a parametric family of cubic polynomials

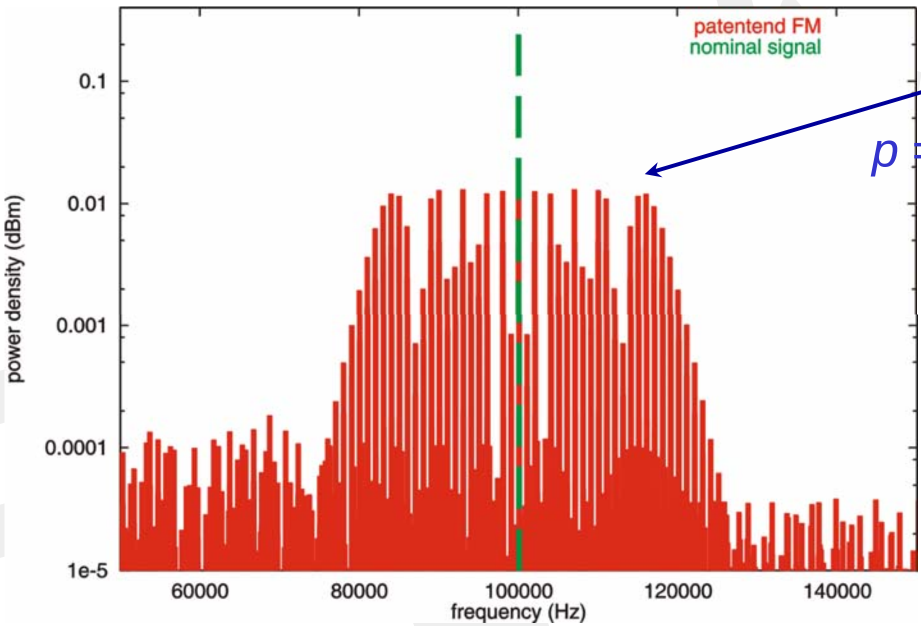
$$c_b(x) = 16(4 - p)x^3 + px, \;\; x \in [-1/4, 1/4]$$

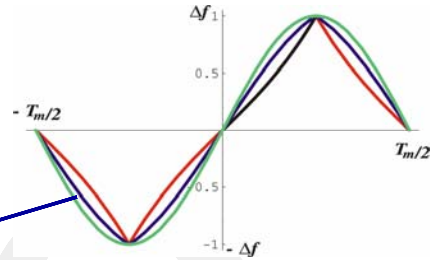
to construct the modulating waveform



… and a better one - II

• Optimal choice of the parameter $p \Longrightarrow$ almost flat spectrum





$p = 4.12$

f_0=100KHz, f_m=1Khz, m=20

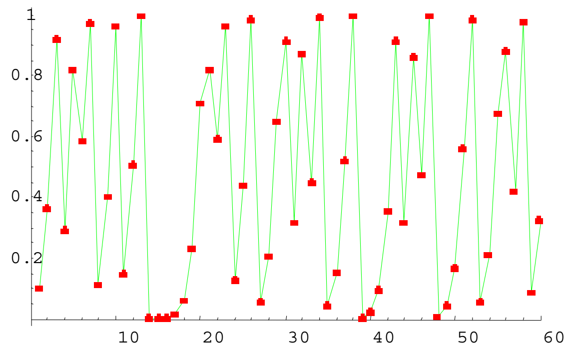
… but the frequency modulation law is always periodic

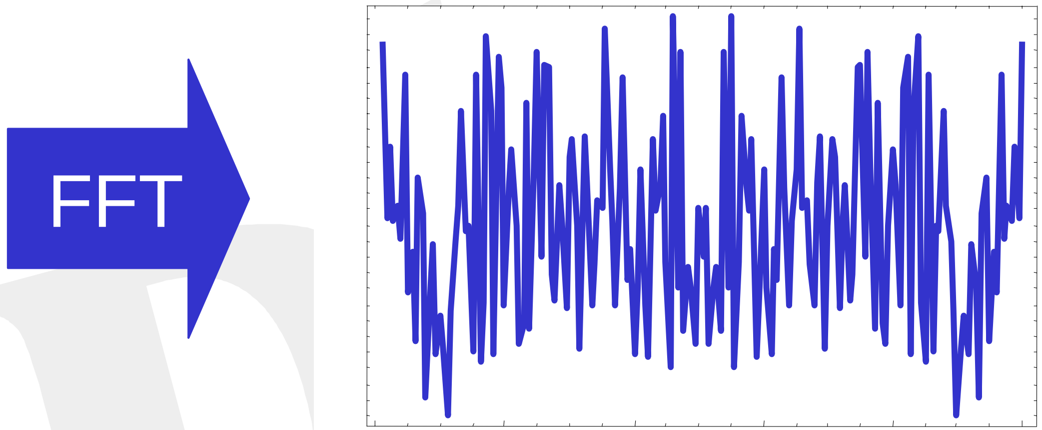
$\Longrightarrow$ the modulated signal does not have a continuous spectrum

$\Longrightarrow$ power is densely concentrated around specific frequencies

An non periodic modulating signal would be better!

Can chaos be even better for EMI reduction?

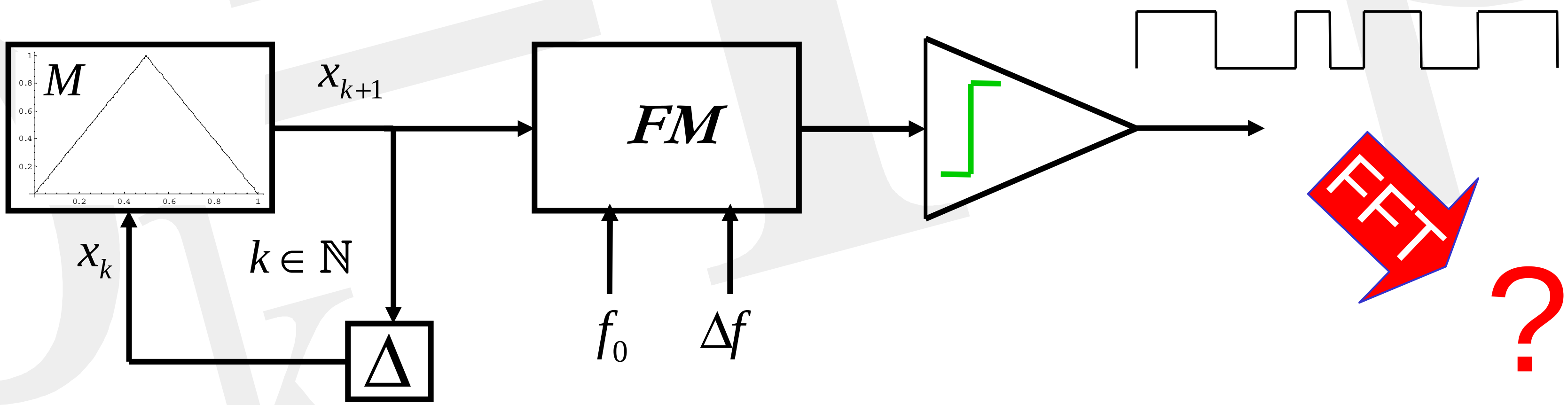




Broadband noiselike

- Chaotic map $x_{k+1} = M(x_k) \quad k \in \mathbb{N}$

  with $M : X = [-1,1] \mapsto [-1,1]$ and $x_0 \in [-1,1]$



Which is the shape of the power spectrum?

Spectrum of perfectly random FM - I

• Modulating PAM signal $\xi_m(t) = \sum_{k=-\infty}^{\infty} x_k g(t-kT_m)$ where x_k are independent random variables drawn according to a density $\bar{\rho}$

$g(t)$ is the unit rectangular pulse defined in $[0,T_m[$

• Consider a sinusoid (clock fundamental) that is frequency modulated by random PAM

$$c(t) = \cos\left[2\pi\left(f_0 t + \Delta f \int_{-\infty}^{t} \xi_m(\vartheta) d\vartheta\right)\right]$$

• Compute power density spectrum for equivalent low-pass signal

$$\Phi_{\tilde{c}\tilde{c}}(f) = \mathfrak{F}\left[C_{\tilde{c}\tilde{c}}(\tau)\right] = \mathfrak{F}\left[\frac{1}{2T}\int_0^T \mathbf{E}\left[\tilde{c}^*(t)\tilde{c}(t+\tau)\right]dt\right]$$

• Power density spectrum can be expressed as

$$\Phi_{\tilde{c}\tilde{c}}(f) \simeq \Phi_{\tilde{c}\tilde{c}}(f - f_0)$$

Spectrum of purely random FM - II

Main results

1. $$\Phi_{\tilde{c}\tilde{c}}(f) = \mathbf{E}_x\left[K_1(x,f)\right] + \mathrm{Re}\left[\frac{\mathbf{E}_x{}^2\left[K_2(x,f)\right]}{1-\mathbf{E}_x\left[K_3(x,f)\right]}\right]$$

$$K_1(x,f) = \frac{1}{2}\frac{m}{\Delta f}\mathrm{sinc}^2\left(\pi m\left(\frac{f}{\Delta f} - x\right)\right)$$

$$K_1(x,f) = i\,\frac{e^{-i2\pi m(f/\Delta f - x)} - 1}{2\pi\sqrt{m/\Delta f}\,(f - x\Delta f)}$$

$$K_3(x,f) = e^{-i2\pi m(f/\Delta f - x)}$$

General analytical expression for $\Phi_{\tilde{c}\tilde{c}}(f)$ as a function of $\bar{\rho}$ for any value of m

Low-pass operator applied to $\bar{\rho}$

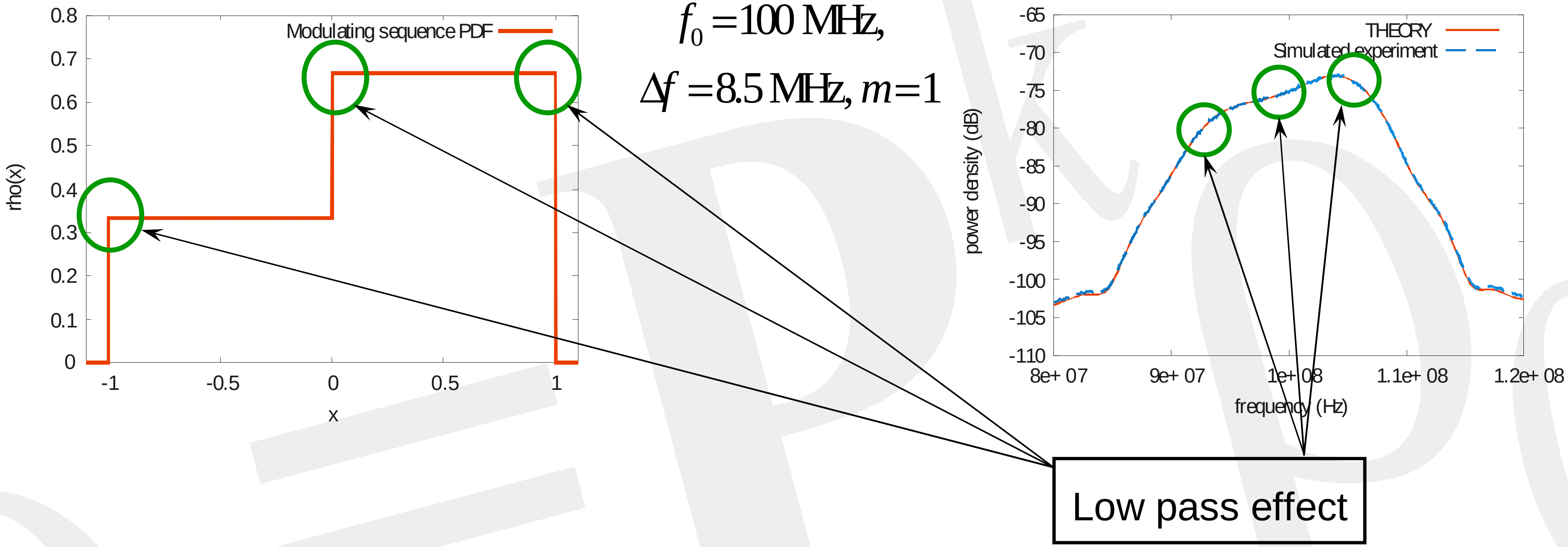
2. $$\lim_{m\to\infty}\Phi_{\tilde{c}\tilde{c}}(f) = \frac{1}{2\Delta f}\bar{\rho}\left(\frac{f}{\Delta f}\right)$$

For large m (slow modulation) $\Phi_{\tilde{c}\tilde{c}}(f)$ has the same shape as $\bar{\rho}$

An interesting example

Low pass operator effect

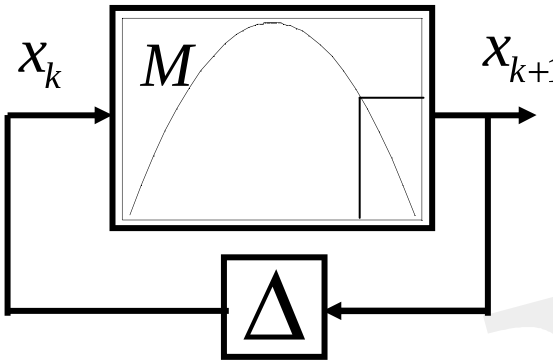
$$f_0 = 100\ \text{MHz},$$
$$\Delta f = 8.5\ \text{MHz},\ m = 1$$



… and with chaotic samples?

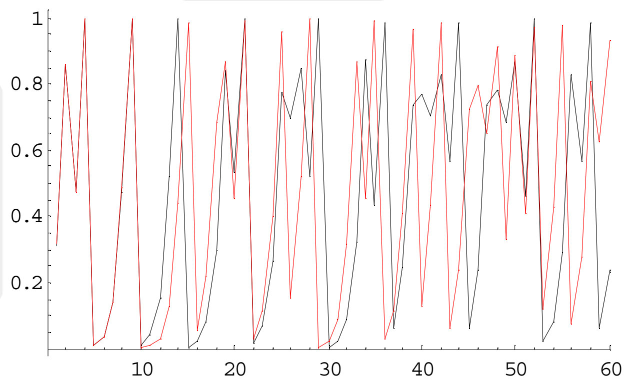
To “implement” random source with the chaotic one, we need to assure that to get the same results!

An alternative approach for studying chaos



- Chaotic map $x_{k+1} = M(x_k) \quad k \in \mathbb{N}$
  with $M : X = [0,1] \mapsto [0,1]$ and $x_0 \in [0,1]$

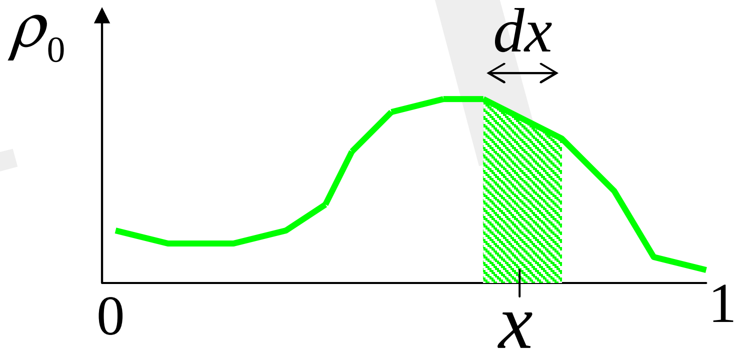
- Evolution of points
  - following single trajectories
    $x_0, x_1 = M(x_0), x_2 = M(x_1), \cdots$ is difficult
  - sensitive dependence on initial conditions
    $x_0^{'} = \pi/10, \; x_0^{''} = \pi/10 + 10^{-4}$



- Evolution of densities

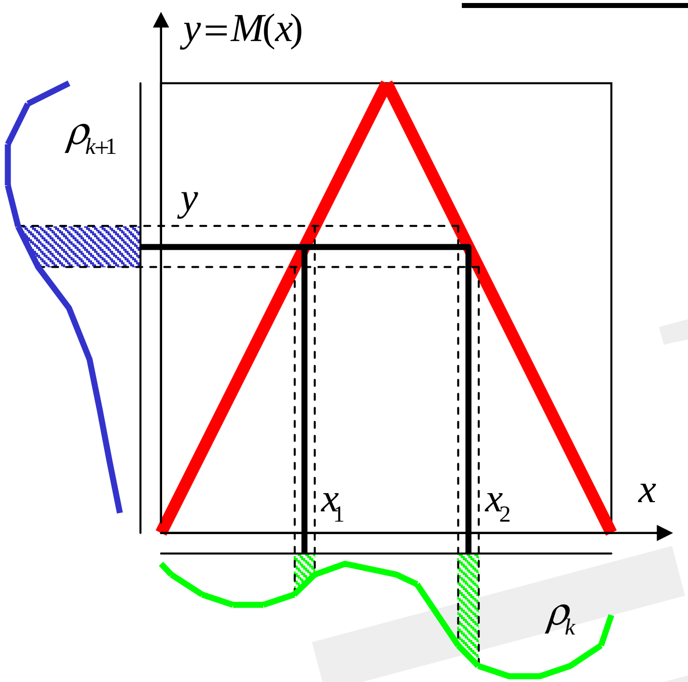
  $\rho_0 : [0,1] \to \mathbb{R}^+$

$$\Pr\{x - dx/2 \le x_0 \le x + dx/2\} = \rho_0(x)dx$$



If x_0 is drawn according to ρ_0, which is the density of $x_1 = M(x_0)$, $x_2 = M(x_1)$,...?

Evolution of densities: Perron-Frobenius operator



Probability conservation constraint:

$$\Pr\left\{ y - \tfrac{dy}{2} \le y \le y + \tfrac{dy}{2} \right\} =$$

$$\Pr\left\{ x_1 - \tfrac{dx_1}{2} \le x_1 \le x_1 + \tfrac{dx_1}{2} \right\} + \Pr\left\{ x_2 - \tfrac{dx_2}{2} \le x_2 \le x_2 + \tfrac{dx_2}{2} \right\}$$

$$\rho_{k+1}(y)dy = \rho_k(x_1)dx_1 + \rho_k(x_2)dx_2 \;\Rightarrow\; \rho_{k+1}(y) = \rho_k(x_1)\frac{dx_1}{dy} + \rho_k(x_2)\frac{dx_2}{dy} \;\Rightarrow\; \rho_{k+1}(y) = \frac{\rho_k(x_1)}{|M'(x_1)|} + \frac{\rho_k(x_2)}{|M'(x_2)|}$$

Perron-Frobenius operator $\mathbf{P}_M$ of *M* for maps with "several branches"

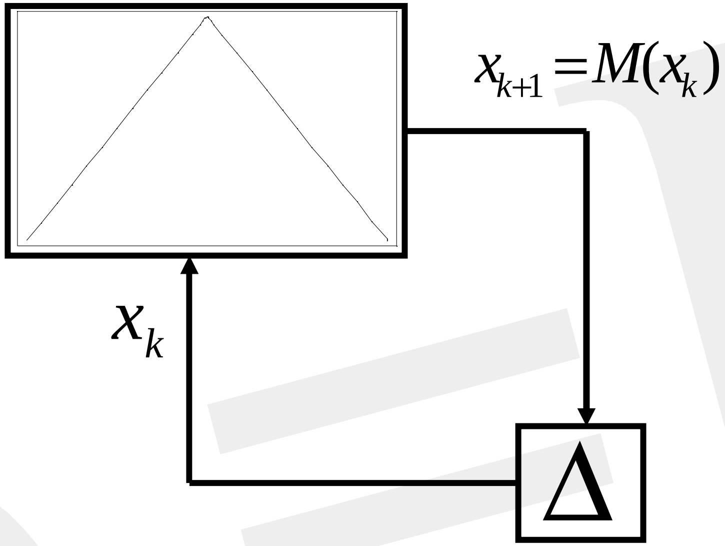
$$\rho_{k+1}(y) = \mathbf{P}_M \rho_k(y) = \sum_{M(x)=y} \frac{\rho_k(x)}{|M'(x)|}$$

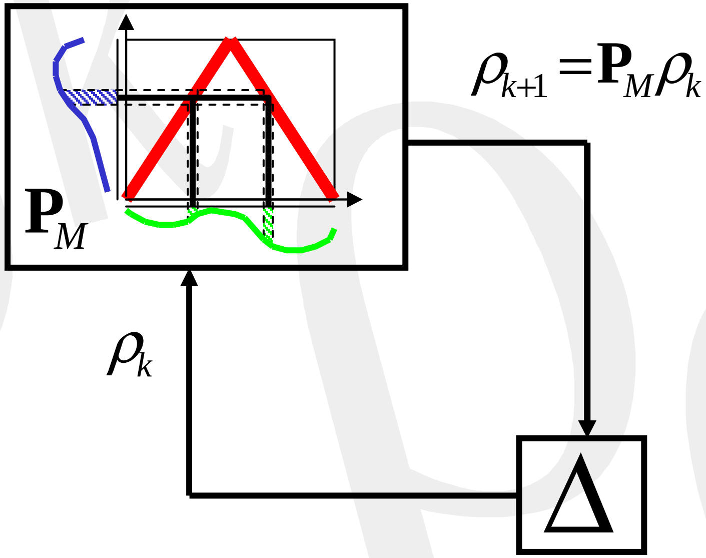
Linear functional operator

A Global Linearization

$$x_k = \underbrace{M \circ M \circ \cdots \circ M}_{\text{k-times}}(x_0) = M^k(x_0)$$

$$\rho_k = \mathbf{P}_{M^k}\rho_0 = \mathbf{P}_M{}^k \rho_0$$



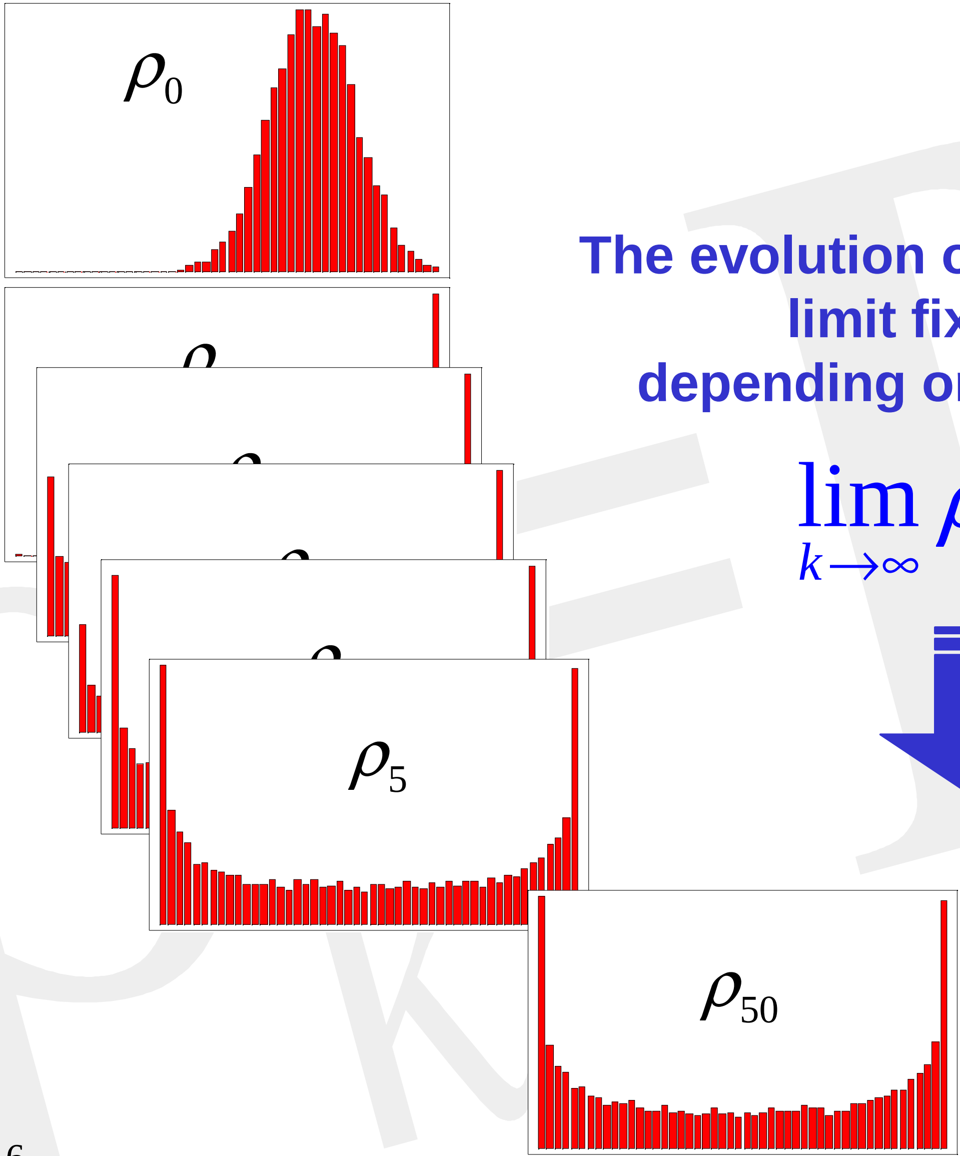


- ☺ Finite dimension (one)
- ☹ Highly Nonlinear
- ☹ Extremely Complex

- ☺ Linear
- ☺ “Simple” (Regular) Behavior
- ☹ Infinite Dimensions (not always…)

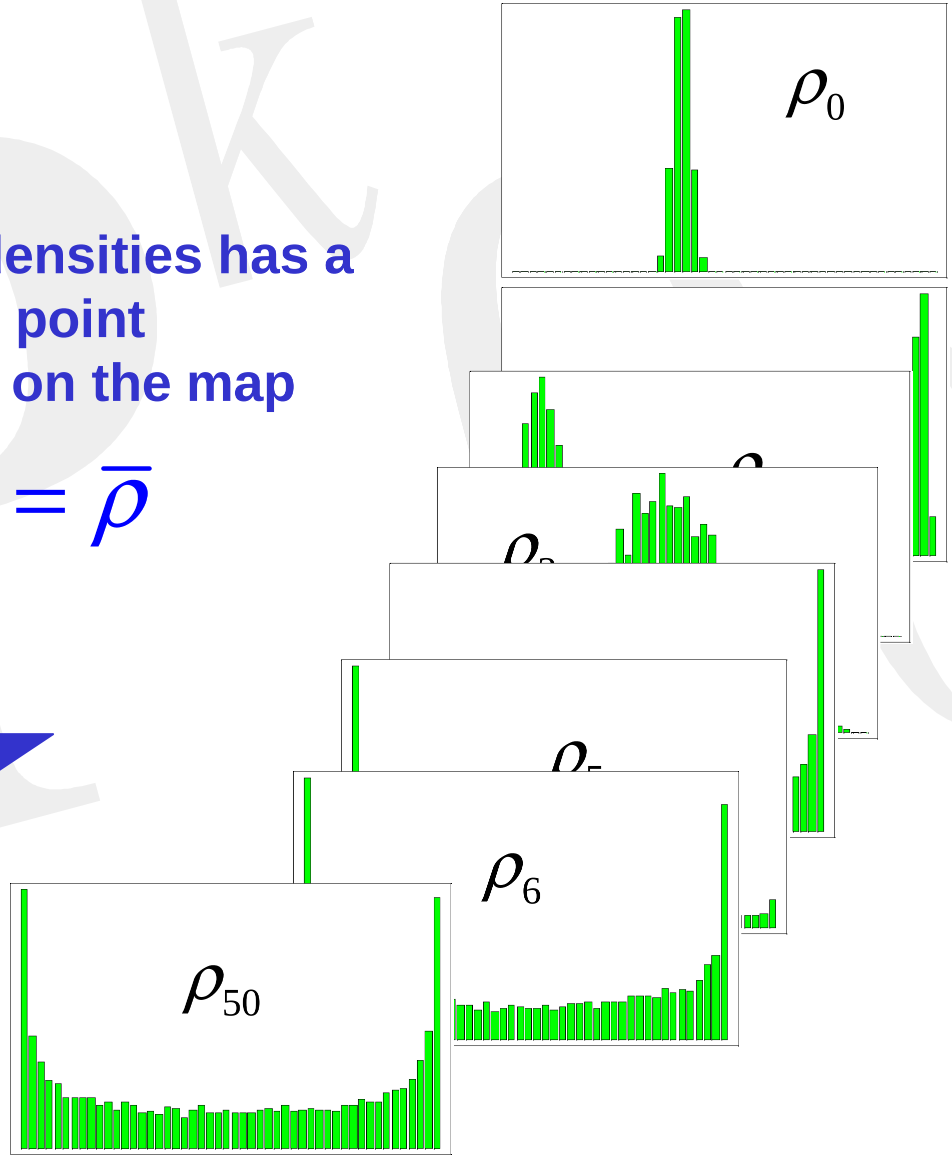
Can we say something on the behavior of the “linearized system”?

An example



The evolution of densities has a limit fixed point depending only on the map

$$\lim_{k\to\infty} \rho_k = \bar{\rho}$$



Properties of the linearized system

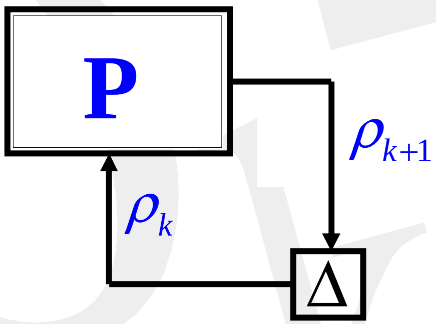
Chaotic systems are deterministic! … but can be studied with statistical tools

For any ρ_0 we know that $\boxed{\lim_{k\to\infty} \rho_k = \bar{\rho}}$

Two important points

How to compute $\bar{\rho}$?

How fast $\rho_k \to \bar{\rho}$?

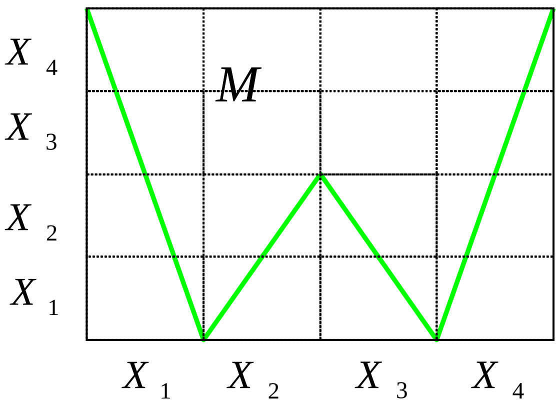


$$\bar{\rho} = \mathbf{P}\,\bar{\rho}$$

$$\left\| \rho_k - \bar{\rho} \right\| \le C r_{\text{mix}}^k \xrightarrow{k\to\infty} 0$$

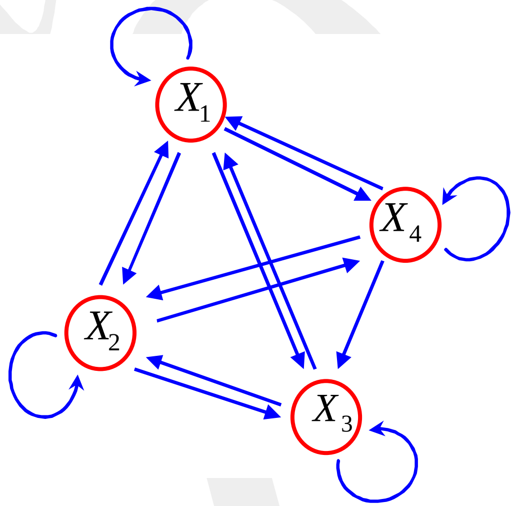
Difficult to be computed in general…

Statistical approach for PWAM maps



- Markov partition: $X_1, \cdots, X_n$ such that

$$X_j \subseteq M(X_k) \text{ or } \mu(X_j \cap M(X_k)) = 0 \ \forall j,k$$

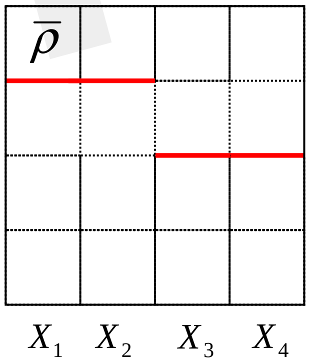


- **Kneading matrix (Transition matrix)**

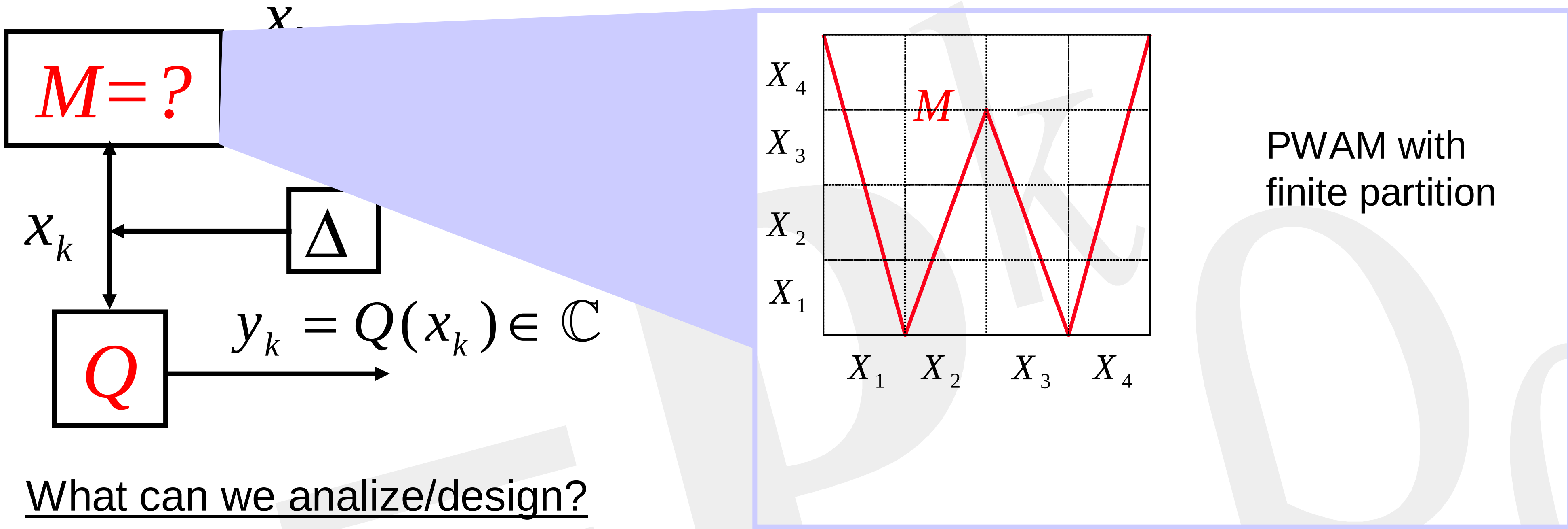
$$\mathcal{K}_{jk} = \frac{\mu\left(X_j \cap M^{-1}(X_k)\right)}{\mu\left(X_j\right)} = \begin{cases} \text{Fraction of } X_j \text{ which is mappend in } X_k \\ \text{Probability } (\mu) \text{ that } x \text{ moves } X_j \to X_k \text{ given that it is in } X_j \end{cases}$$

- The invariant density of PWAM maps is piece-wise constant
  - For such maps $\mathcal{K} \approx \mathbf{P}$
  - To compute $\bar{\rho}$ one computes the left eigenvector $\underline{\alpha}$ of $\mathcal{K}$

$$\underline{\alpha} = \underline{\alpha}\mathcal{K} \qquad \underline{\alpha}_W = (3/4, 3/4, 1/4, 1/4)$$



- Moreover $r_{\text{mix}} = \max\{|\lambda|, F(\text{map slopes})\}$ $\qquad r_{\text{mix}} = 1/2$



What can we analize/design?

- Probability density *(i.e. how often a certain value appears in the process history)*
- Rate of mixing *(i.e. how fast the probability describing the distribution of the state converges to the invariant one)*
- Exact finite time crosscorrelation profile *(i.e. how each realization of the process is related to other realizations of the same process)*
- Exact finite time autocorrelation *(i.e. the short-time power spectral density of the process)*
- Asymptotic trend of autocorrelation *(i.e. power spectral density at low frequencies: exponential trend, polynomial trend, combinations)*
- Higher order moments/correlation *(i.e. how multiple samples from the process relate to each other)*

Spectrum of chaotic FM - I

- Chaotic map generates the samples $\{x_k\}$

Main results (Proc IEEE 2002, TCAS-I, 2003)

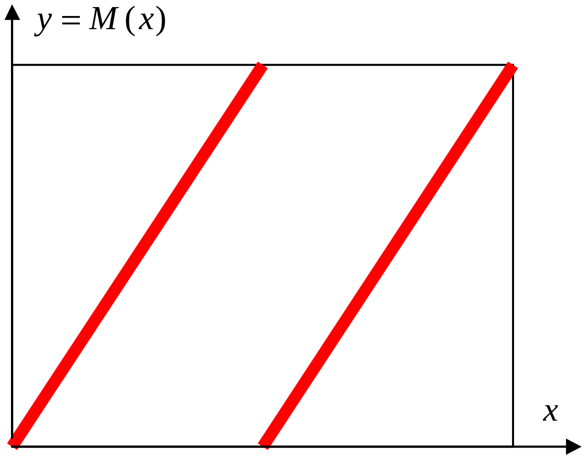
1. $$\lim_{r_{\text{mix}} \to 0} \Phi_{\tilde{c}\tilde{c}}(f) = \mathbf{E}_x\left[K_1(x, f)\right] + \text{Re}\left[\frac{\mathbf{E}_x{}^2\left[K_2(x, f)\right]}{1 - \mathbf{E}_x\left[K_3(x, f)\right]}\right]$$

If r_{mix} low chaotic samples approximate purely random variables

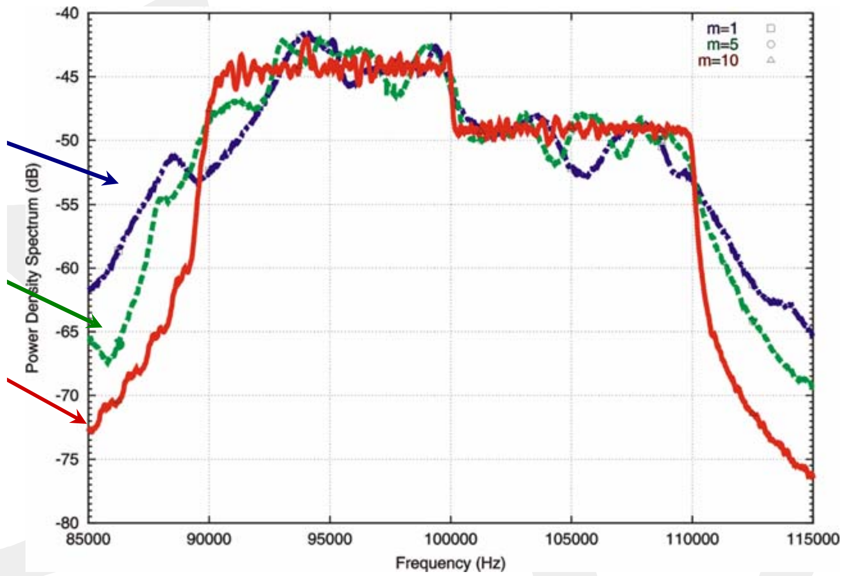
2. $$\lim_{m \to \infty} \Phi_{\tilde{c}\tilde{c}}(f) = \frac{1}{2\Delta f}\,\bar{\rho}\left(\frac{f}{\Delta f}\right) \qquad \forall f \text{ such that } \nexists k \; M^k\left(\frac{f}{\Delta f}\right) = \frac{f}{\Delta f}$$

For slow modulation $\Phi_{\tilde{c}\tilde{c}}(f)$ has the same shape as $\bar{\rho}$
for all frequencies not corresponding to fixed points of (iterate of) map

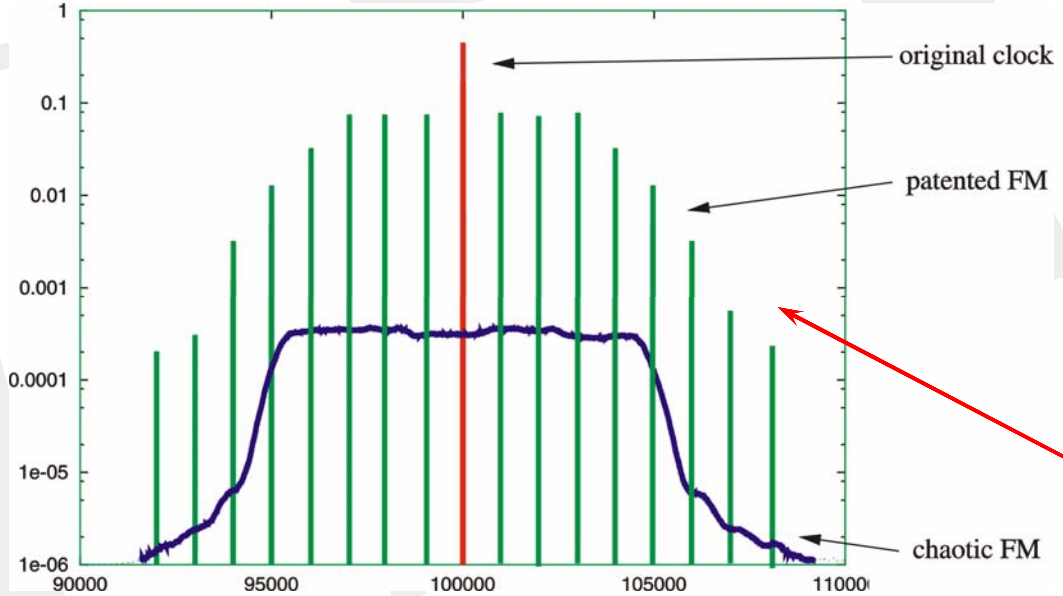
Spectrum of chaotic FM - II



$\bar{\rho}(x) = 1/2$ $\qquad r_{mix} = 1/2$



f_0=100KHz, f_m=1Khz, m=10, resolution 4Hz



An easy optimal solution

- For slow modulation

Maximum spreading (peak reduction)

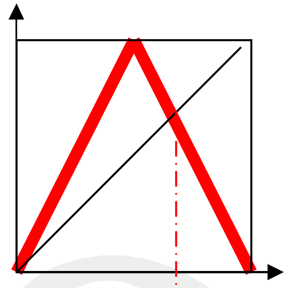
$\Downarrow$

Uniform density

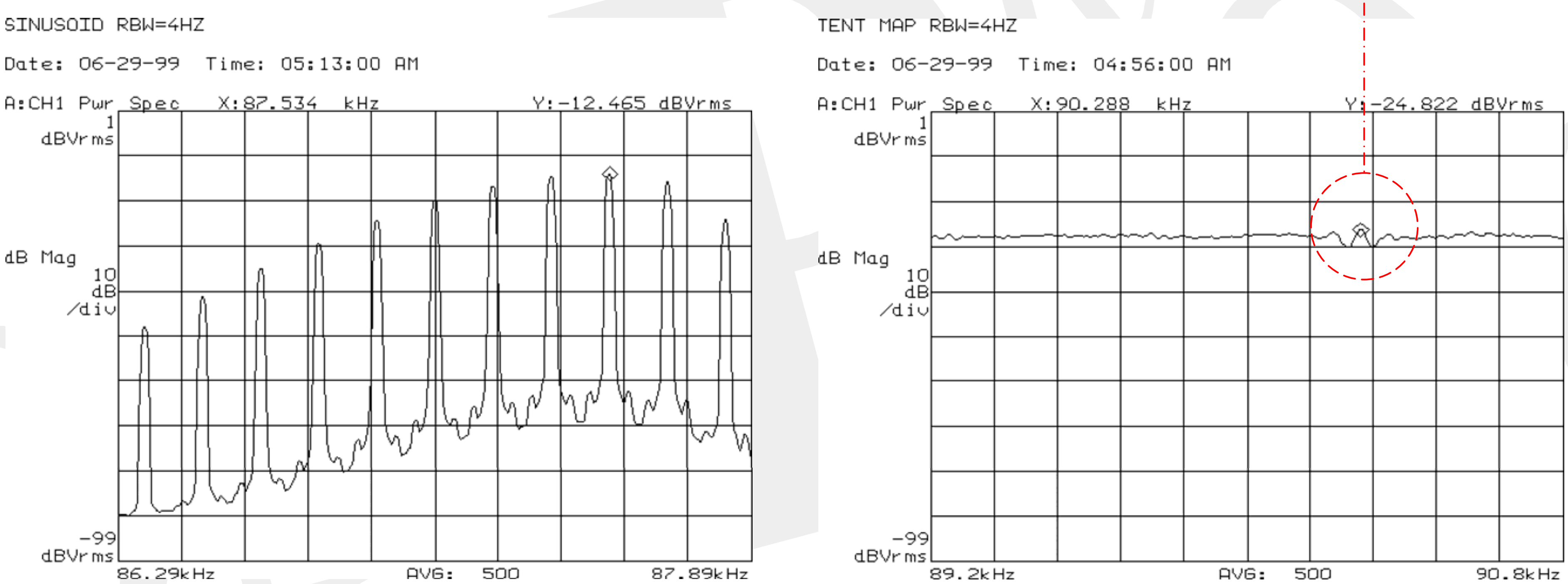
improvement of ≈ 16dB

Spectrum of chaotic FM : experimental results - I

- Tent map implementation with of-the-shelf components



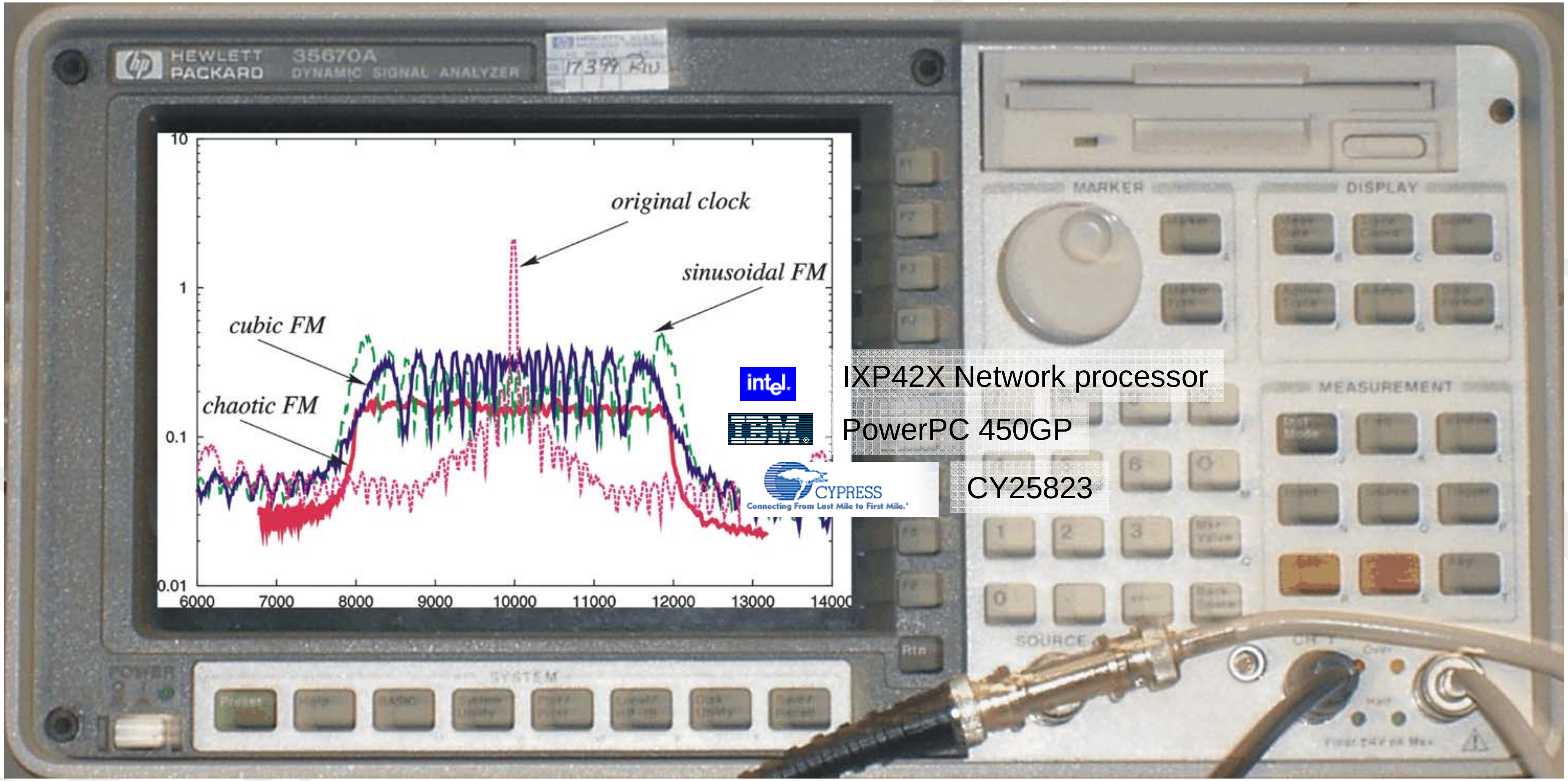
- f_0=100KHz, f_m=150Hz, m=15, with a HP35670A – digital SA with RBW=4Hz



- Reduction of ≈ 13dB with respect to the sinusoidal FM

CB-reduction of timing signal generated EMI

• f_0=10KHz, f_m=50Hz, m=40, with a HP35670A – digital SA with RBW=8Hz



9dB peak reduction with respect to the best known and patented method

Problems - I

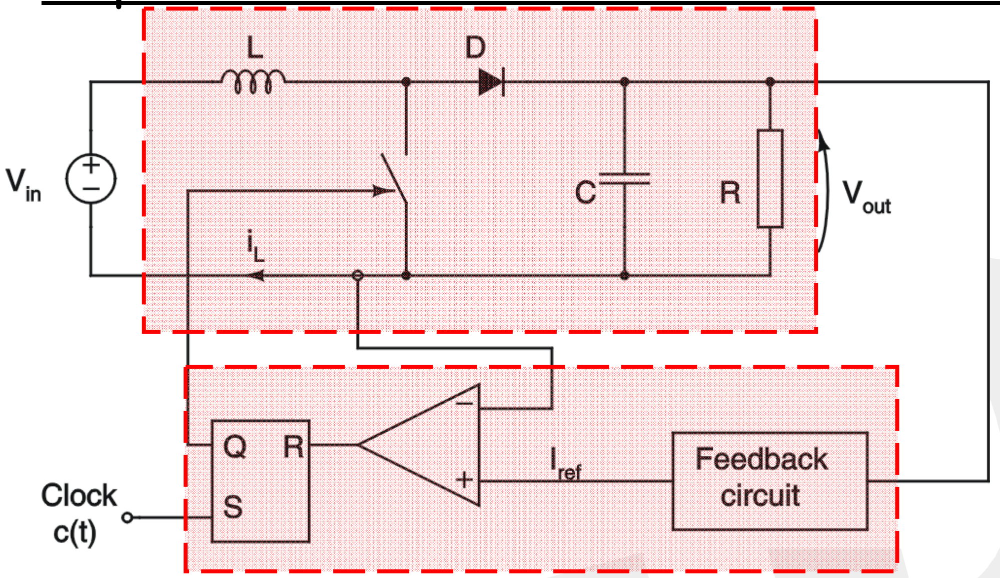
- Methods for reducing EMI due to periodic timing signals
  - Sinusoidal FM
  - Cubic FM (Lexmark patent)
  - Chaos-based FM
- Measured peak reduction of 9dB with respect to previously patented methods
- Analytical tools for computing power spectrum density of chaotic FM signals

Spectrum of the timing control signal only in case of clocks:

- Does this work also for PWM signals?
- Is the reduction present also for all voltages and currents?
- Does it work with a feedback?

Example of a Boost Current Controlled DC/DC Converter

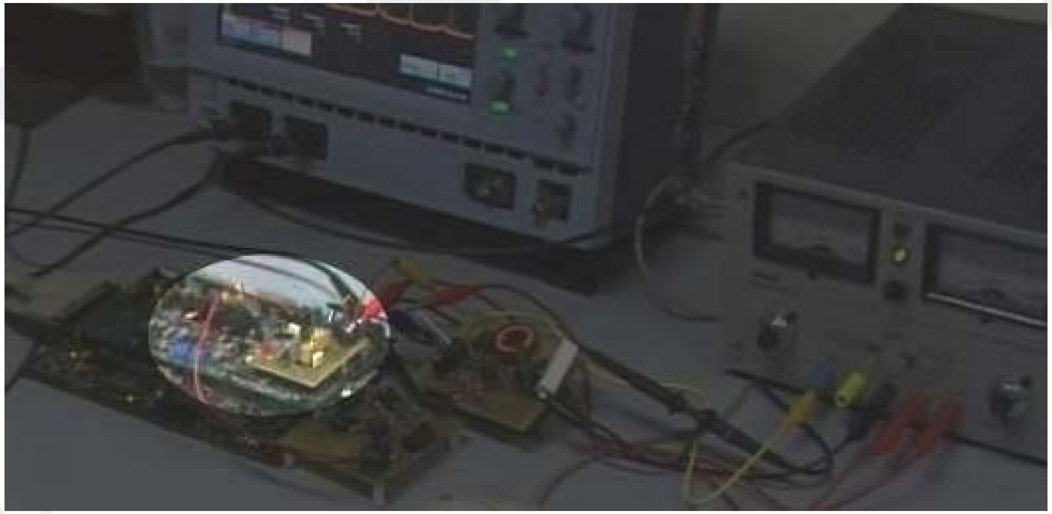
Implementation of a Low EMI Current Feedback Boost DC/DC Converter - I



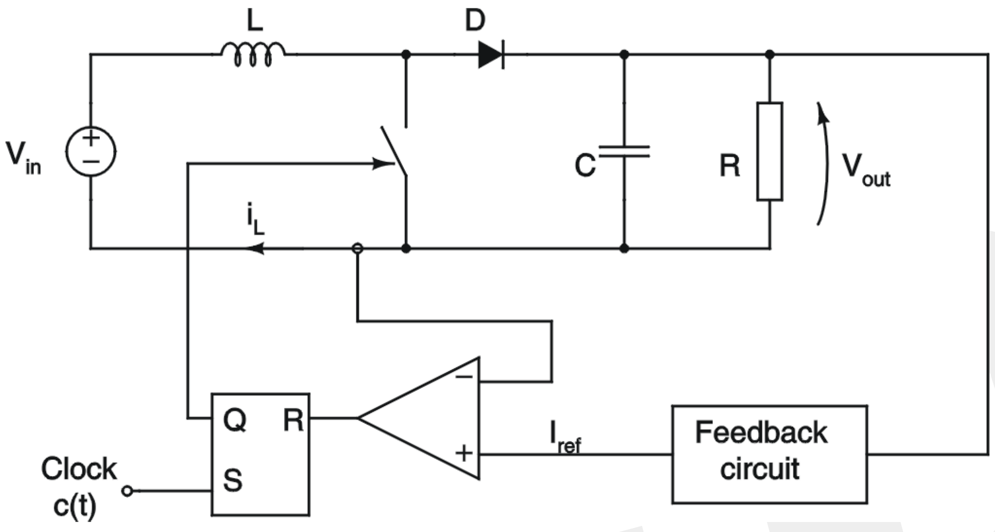
L=1.5 mH	
C = 100 μF	
R = 100 Ω	
NBR1540 power diode	
IRF540 power MOSFET (switch)	
f_0 = 50 kHz	
V_{in} = 6 V	
TMS320C6711 DSP board	

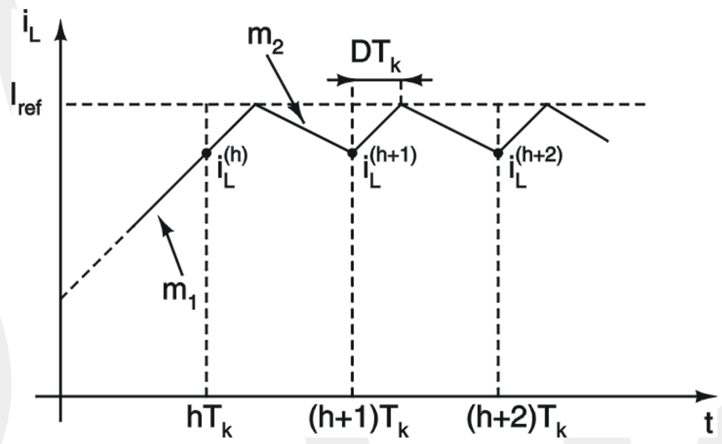
Chaotically

Jittered Clock



Implementation of a Low EMI Current Feedback Boost DC/DC Converter - II





- Feedback is present. How does the converter work?
- Assume "standard behavior", i.e. that c(t) is periodic $(T_k) \Rightarrow$ when c(t) $\rightarrow$ 1, i.e. at h T_k, the switch closes and $i_L(t)\uparrow$ until it reaches I_{ref} when the comparator changes its status, the switch opens and $i_L(t)\downarrow$. The behavior of $i_L(t)$ is periodic and

$$i_L^{(h+1)T_k} \rightarrow I_{ref} - {m_1 m_2}/{m_1 + m_2}\, T_k$$

$\Rightarrow$ we can expect peaks in the PDS!!!

$\Rightarrow$ we need to introduce a jittered clock

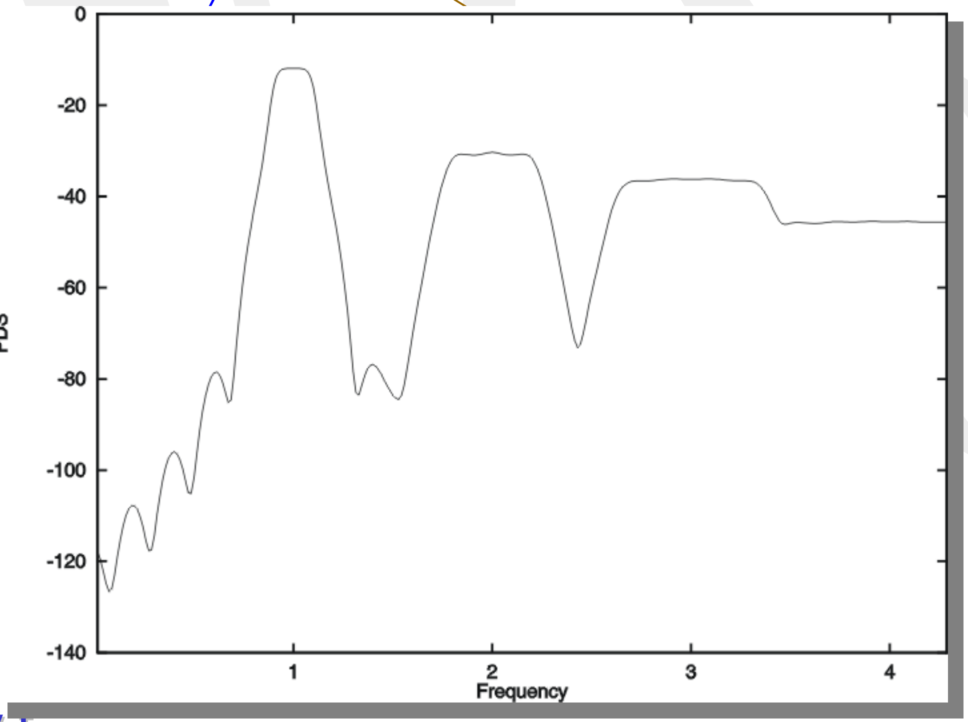
Implementation of a Low EMI Current Feedback Boost DC/DC Converter - III

Estimation of the inductor current PDS

$$\lim_{r_{\text{mix}}\to 0}\Phi(f)=\sum_{h=1}^{\infty}\left\{\mathbf{E}_x\left[K_1^{(h)}(x,f)\right]+\mathrm{Re}\left[\frac{\mathbf{E}_x{}^2\left[K_2^{(h)}(x,f)\right]}{1-\mathbf{E}_x\left[K_3(x,f)\right]}\right]\right\}$$

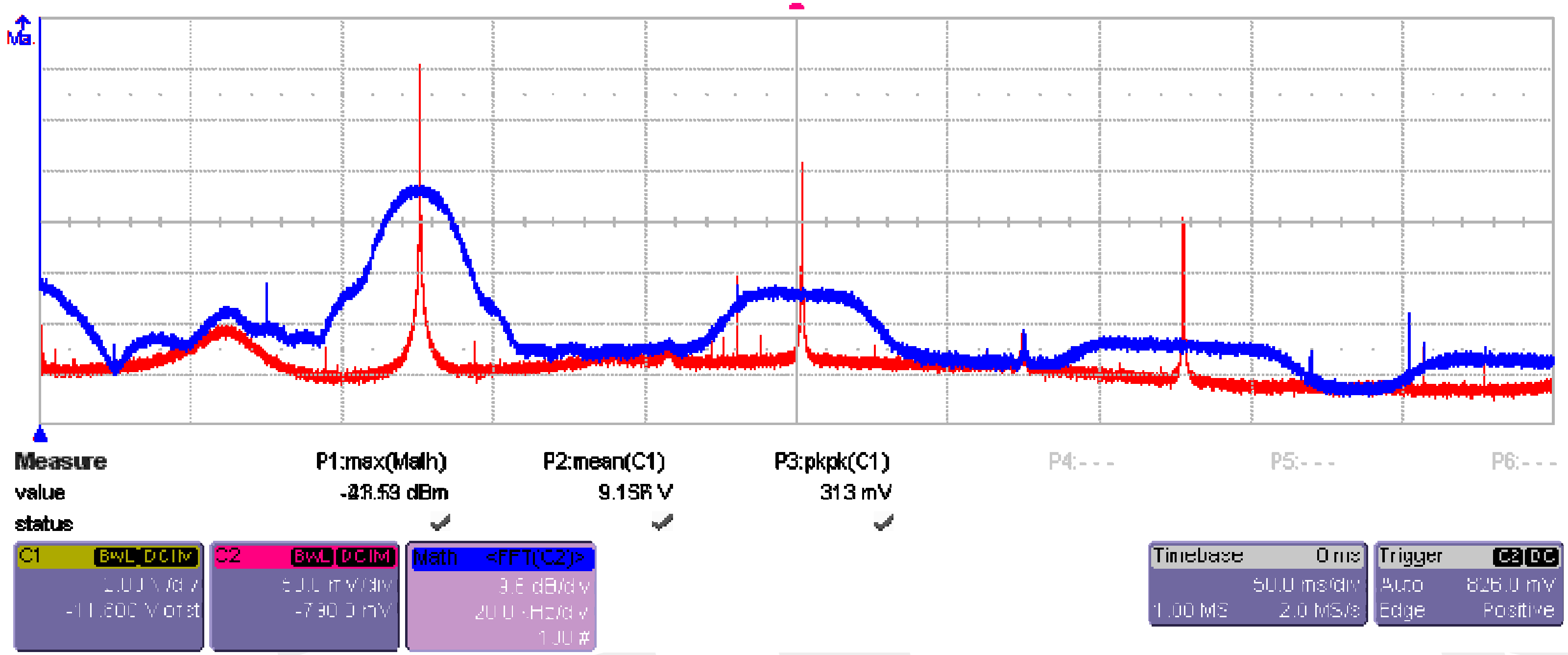
$$K_1^{(h)}(x,f)=\frac{1}{2}\frac{m}{\Delta f}\left|\mathrm{A}_{\mathrm{h}}^{\mathrm{x}}\mathrm{sinc}\left(\pi m\left(\frac{f+hf_0}{\Delta f}-hx\right)\right)\right.$$

$$K_2^{(h)}(x,f)=\sqrt{m/\Delta f}\,e^{-i\pi m\left(f/\Delta f-x\right)}\mathrm{A}_{\mathrm{h}}^{\mathrm{x}}\mathrm{s}$$



Comparing these expressions
inductor current PDS can be e
harmonic forming the spectrur
a periodic regime at frequency f_0

Measurement Results



Periodic Clock

Ripple $= 313mV$

Peak $= -21.2dBm$

High-EMC Chaos-based Clock

Ripple $= 313mV$

Peak $= -43.53dBm$

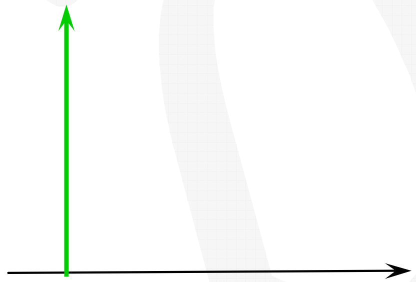
22dB EMI reduction with respect to the conventional case

Ripple performances ***are not affected*** by modulation

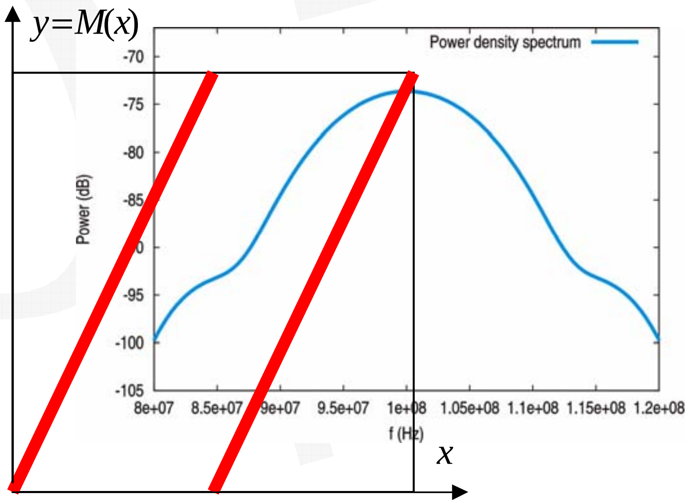
- Methods for reducing EMI due to periodic timing signals
- Measured peak reduction of 9dB with respect to previously patented methods
- Analytical tools for computing power spectrum density of chaotic FM signals
- Methods is applicable for EMI reduction in switching power converters

Slow modulation is a good trick to pass the tests, but real failure is proportional to the energy delivered to the victim!

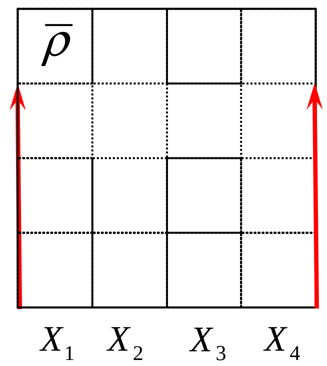
$\Rightarrow$ A fast modulation (low m) would be much better!



- Bernoulli shift f_0=1MHz, Δf=100KHz, m=0.425



Ultimate limit of this idea: *perfectly random binary modulation*



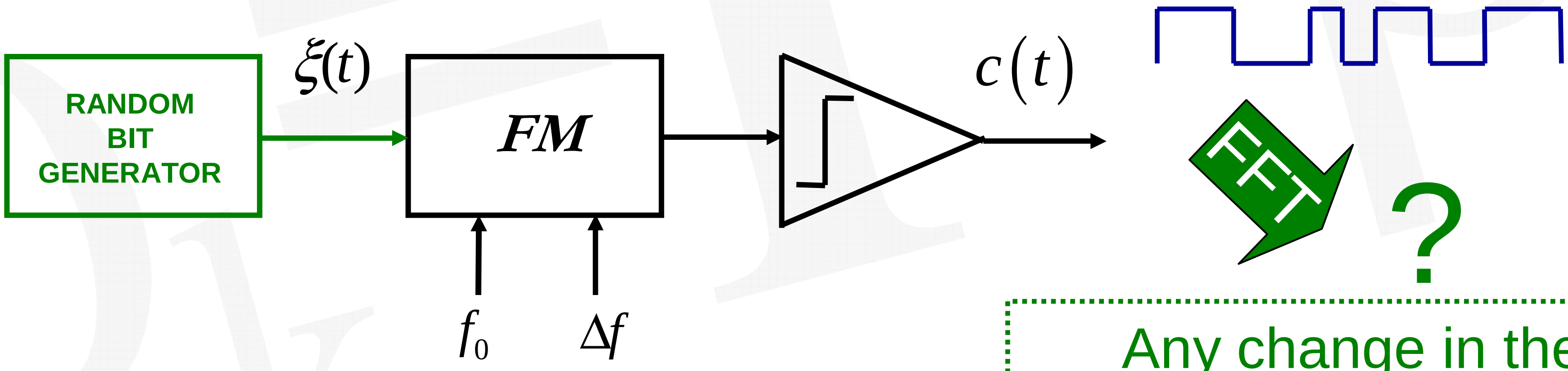
Fast binary FM - I

Among different spread-spectrum techniques, we choose

Fast Binary Random frequency modulation

$$c(t) = \operatorname{sgn}\left(\cos\left[2\pi\left(f_0 t + \Delta f \int_{-\infty}^{t} \xi(\tau)\, d\tau \right) \right] \right),$$ output signal

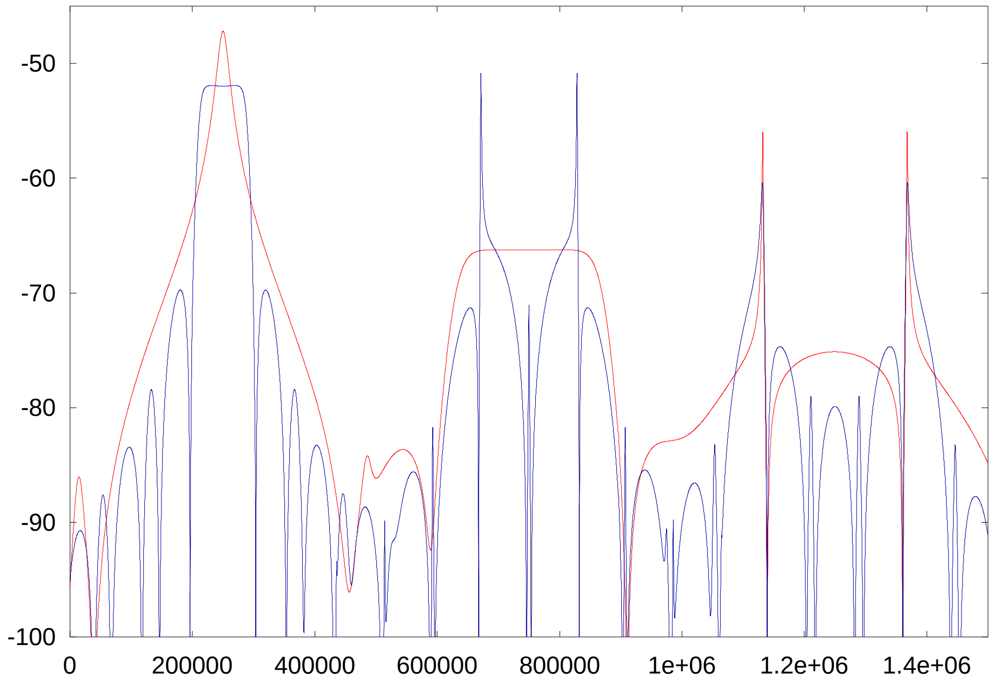
- Fast — T_m short with respect to $1 / \Delta f$
- Binary — driving signal is a PAM signal with only two values
- Random — $\{x_k\}$ random variable which assumes the values $\{0,1\}$ with the same probability $p=0.5$



Any change in the shape of the power spectrum?

Fast binary FM - II

The shape of the spectrum depends on the modulation index



$m = 0.106$

$m = 0.318$

m is set properly to flatten the power spectrum in the desired interval

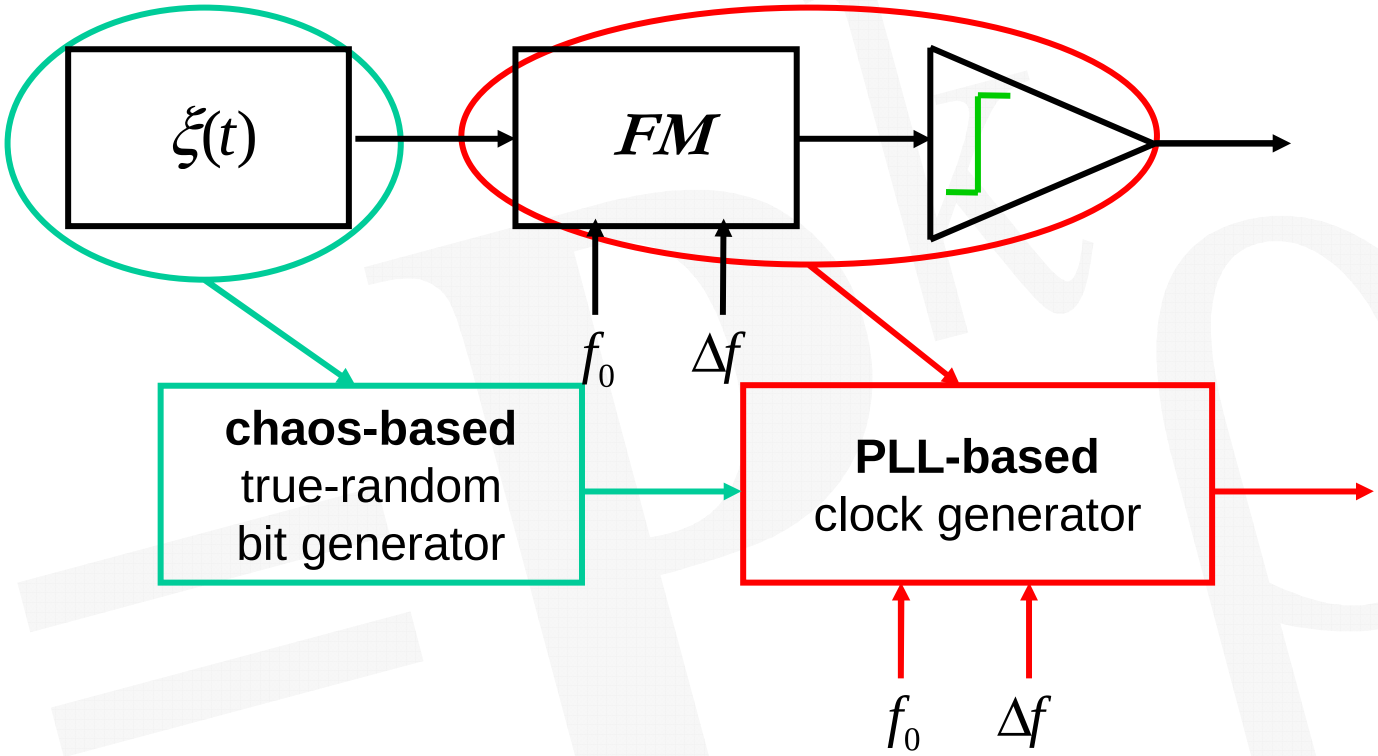
The first harmonic has the highest power content

usually $m = 0.318$

Why do we use this modulation if it still features peaks on the spectrum?

- It is a fast modulation, i.e. the output frequency is maintained unaltered for a very short period of time
- It achieves the best peak reduction on the first harmonic with respect to all other known modulations

The SSCG architecture

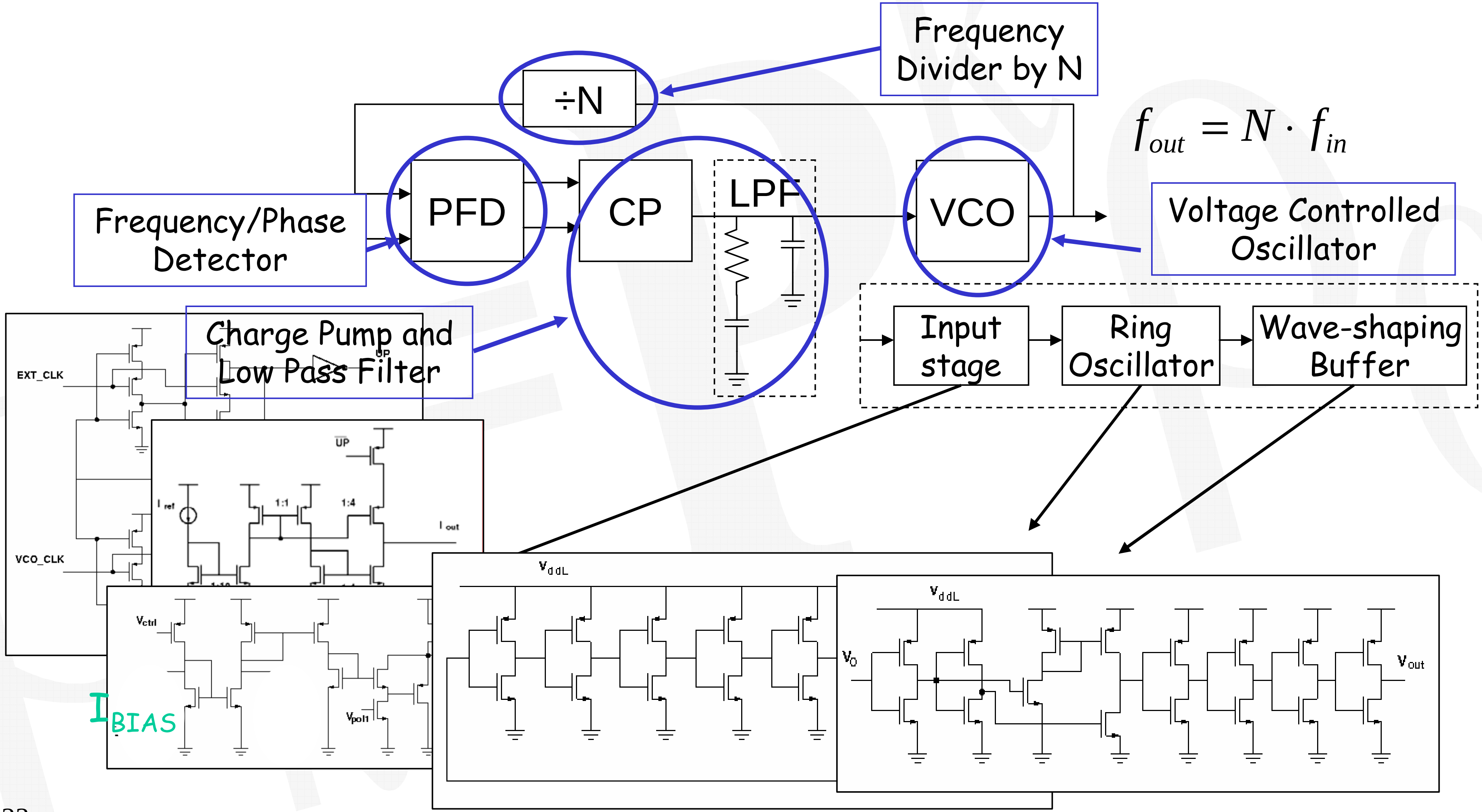


- produces sequences with *very low correlation* (*performances* depends on sequence statistics)
- achieves a very high throughput (we want a *fast* modulation)

- Sets the main frequency with *high precision* (quartz) external clock
- Could perform a frequency multiplier
- *Only few modifications* are required in order to achieve a binary modulator from a standard PLL

PLL-based frequency modulator - I

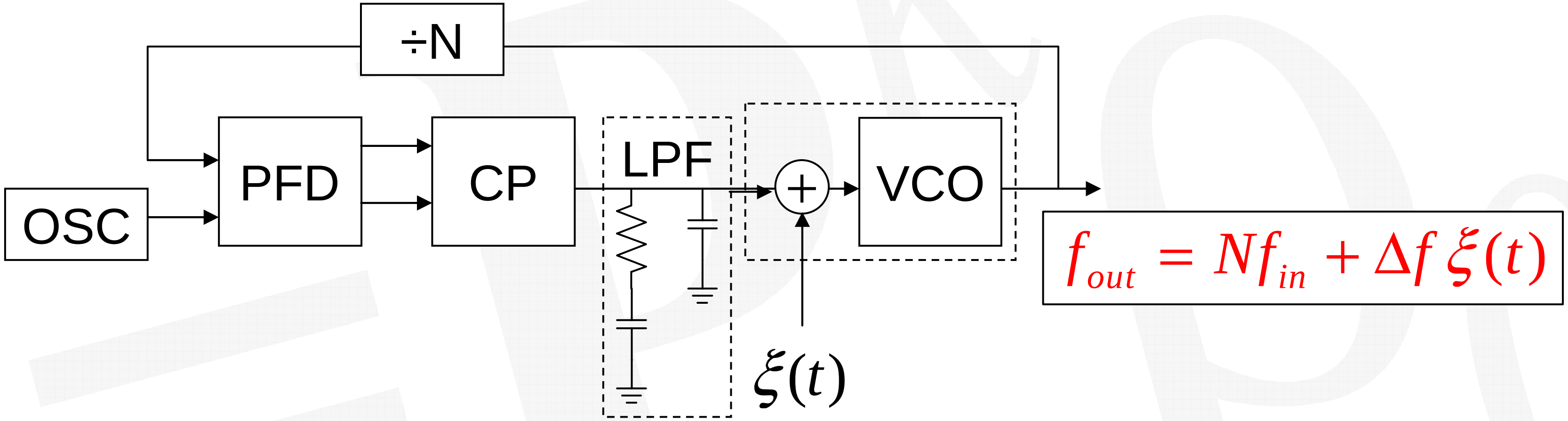
A conventional PLL



$$f_{out} = N \cdot f_{in}$$

PLL-based frequency modulator - II

A conventional PLL has been modified with the interposition of an *analog adder* at the VCO input

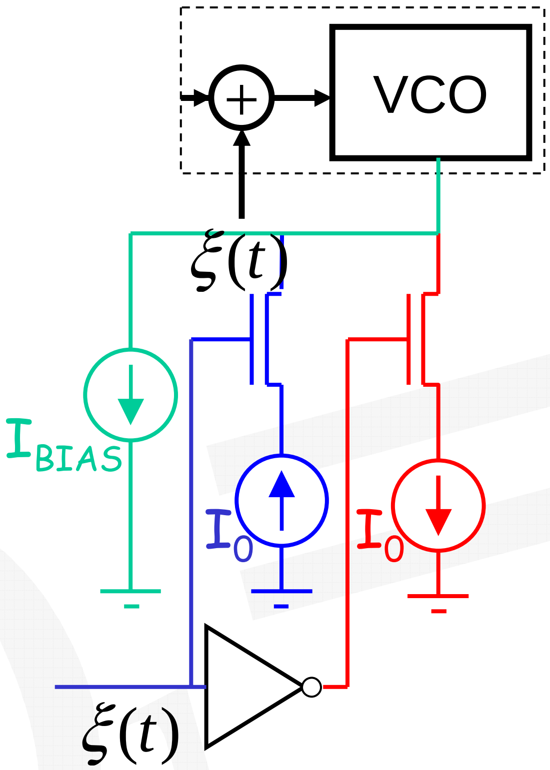


- The driving signal is added to the VCO control voltage, and “*modulate*" directly the output clock
- If the driving signal is *high frequency* with respect to the LPF bandwidth, it cannot pass through the feedback loop.

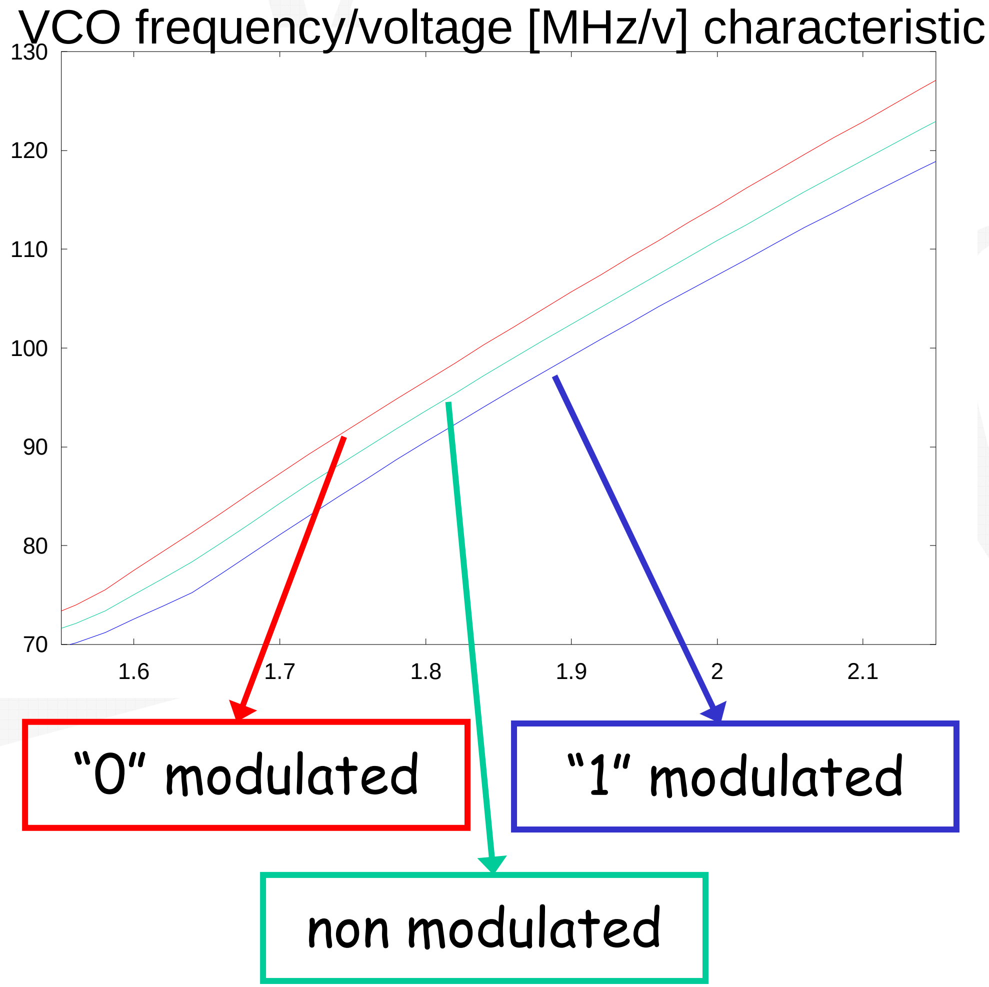
With respect to high frequency driving signals, this circuit behaves as a frequency modulator!

The PLL-based frequency modulator - III

- Since the driving signal is a *digital signal* a full analog adder is not required!!

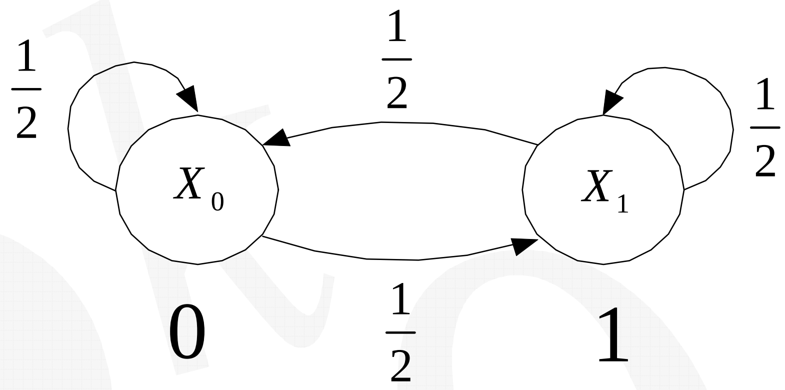


the *digital driving signal* drives two pass-transistors, changing the biasing of the VCO and *shifting* its f/v characteristic

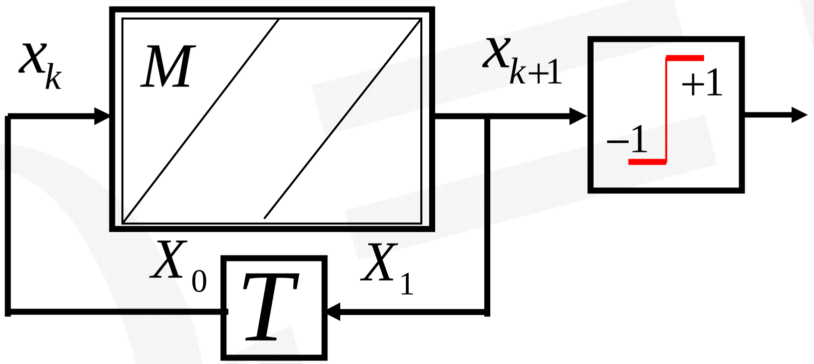


The true-random bit generator - I

Random Bit Generator can be obtained by the following *Markov* chain:



- We based our random bit generator on a simple, chaotic map…



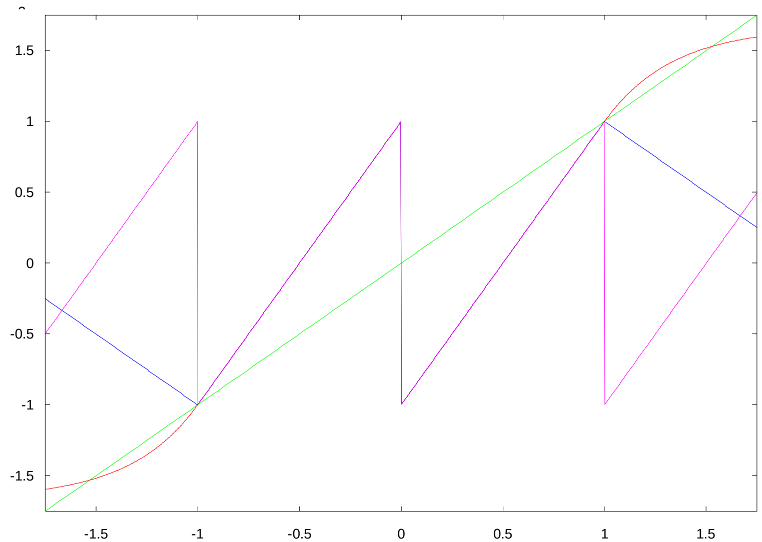
- Chaotic map $x_{k+1} = M(x_k)\ \ k \in \mathbb{N}$

  with $M : I = [-1,1] \mapsto [-1,1]$ and $x_0 \in [-1,1]$

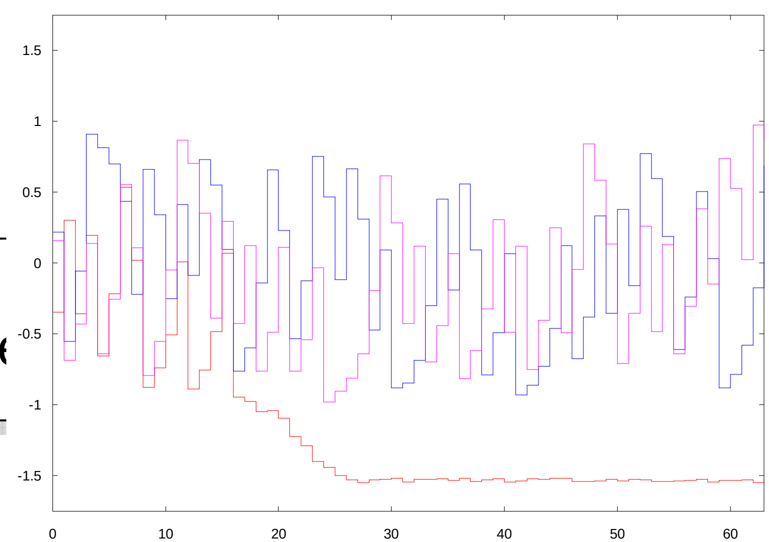
…and obtain a random bit from a quantization of the map state x_k.

Not all chaotic map are suitable for a real implementation!

How to deal with map robustness?



a possible *true-implemented* Bernoulli map



true-implemented systems could reach *stability*

MAP ROBUSTNESS is a fundamental issue!!!

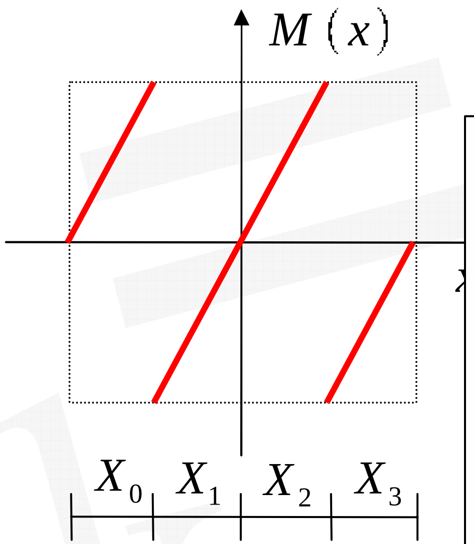
- To prevent parasitic equilibria one introduces suitably defined behavior outside the invariant set: *hooks, tails,…*

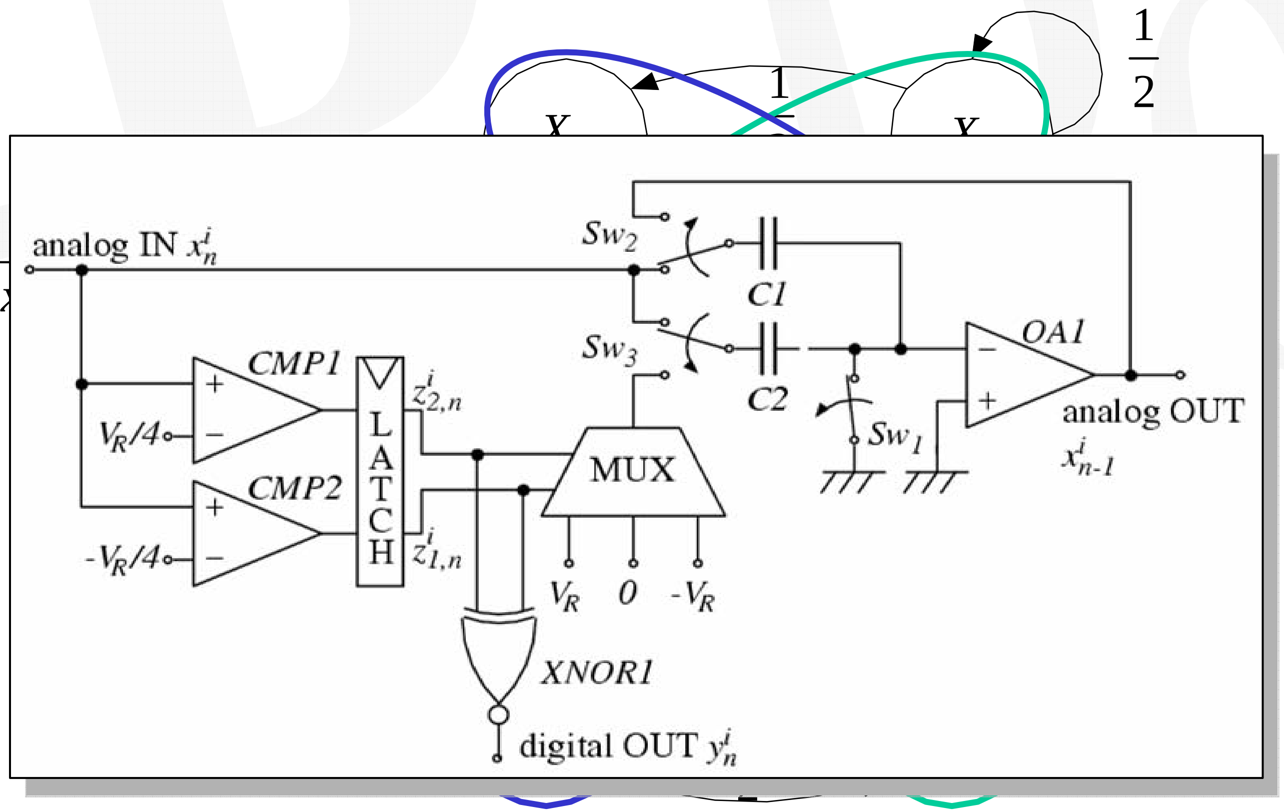
Is there a particularly interesting solution?

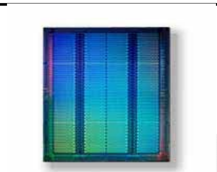
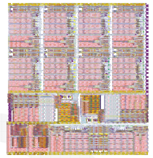
The true-random bit generator - II

The implemented map is the following variation of the Bernoulli map

- It is a **robust map**, i.e. it still maintains the desired behavior even with little implementation error (*analog implementation* is necessary)
- It is a **Markov Map**, i.e. it can be studied through a Markov chain
- A circuit implementing this map is used in **pipeline 1.5 bit/stage ADCs**!





	FPGA True RNG	FPAA Chaotic True RNG	ADC Based True RNG
Randomness source	 Microcosmic (PLL)	 PWAM (reconfig)	 PWAM (ADC)
System Speed	90 MHz	Up to 1 MHz	14 MHz
Random bit Rate	70 Kbit/sec	Up to 1 Mb/s per source (5 per chip)	>**20 Mb/s** **(>100 times faster)**
RNG Conformance for cryptograpic applications	NIST 800-22 in implementation	Unknown	NIST 800-22, 140.2 and DieHard in implementation

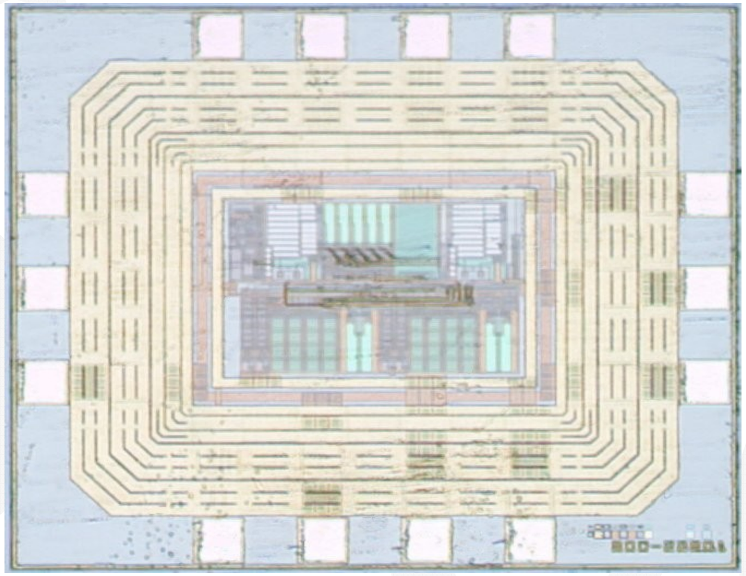
Patent Pending

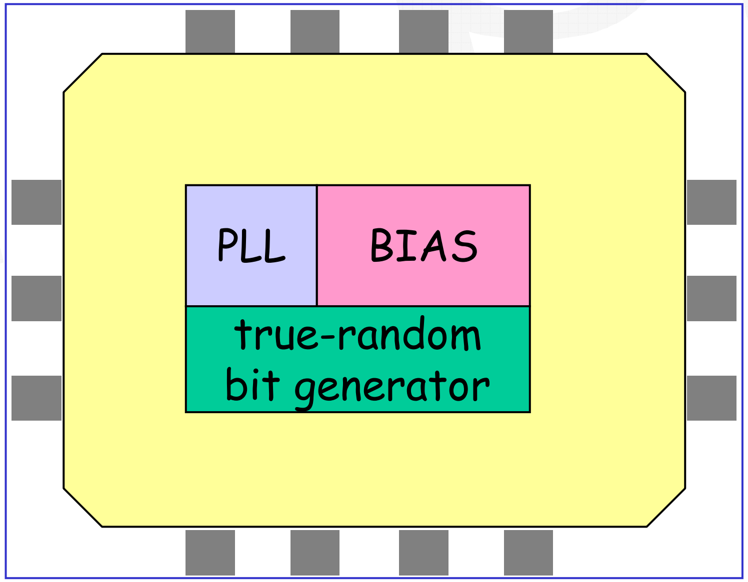
Circuit prototype

A prototype has been implemented in *AMS* CMOS 0.35*μm* technology

Features:

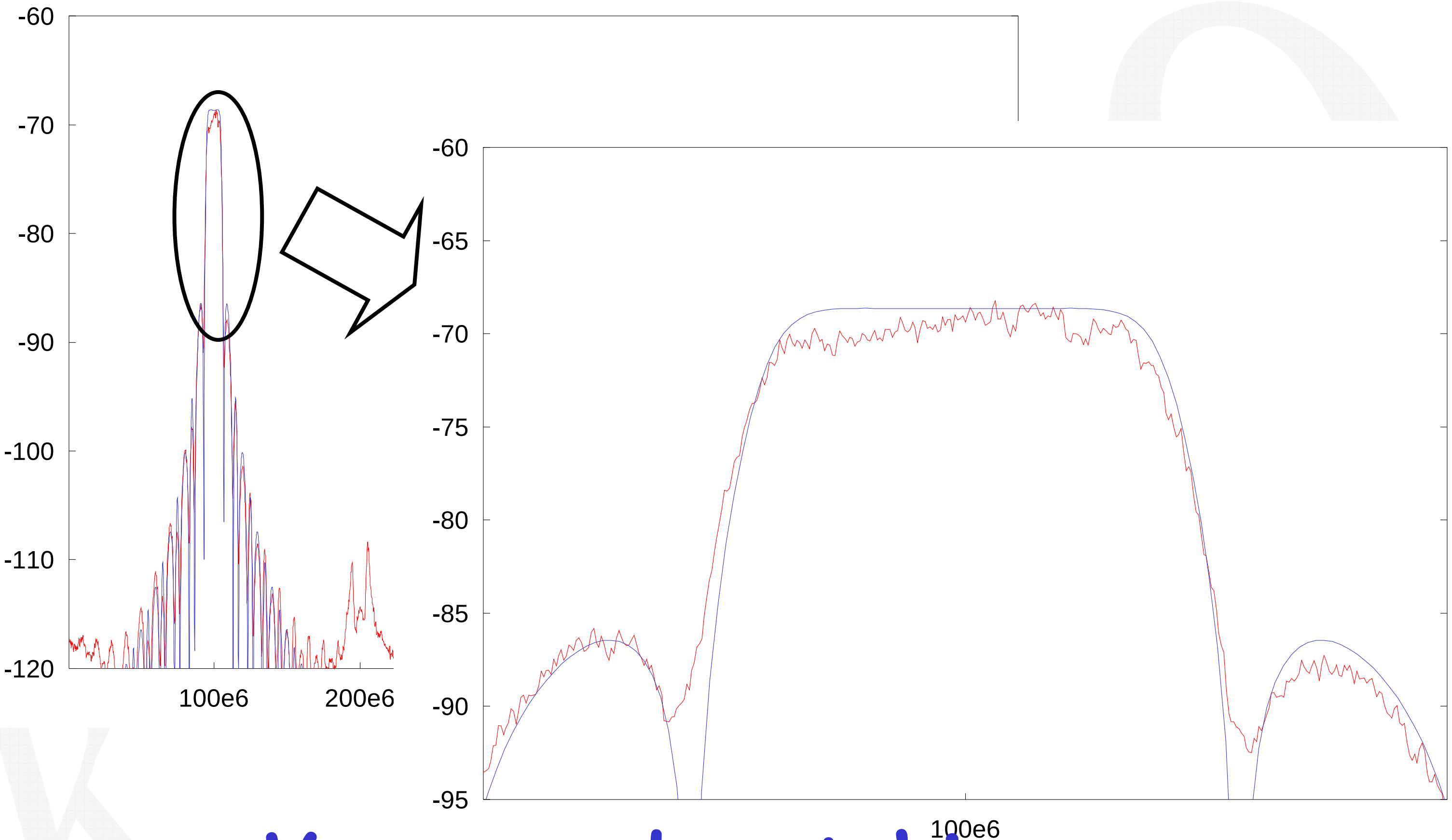
Area	1380 *μm* x 1180 *μm*
Power supply voltage	3.3 *V*
Power consumption	6.2 *mW* (*PLL*) 20.5 *mW* (*whole circuit*)
Typical working frequency	100 *MHz*
Maximum frequency deviation	20 *MHz*
Maximum TRBG working frequency	10 *MHz*





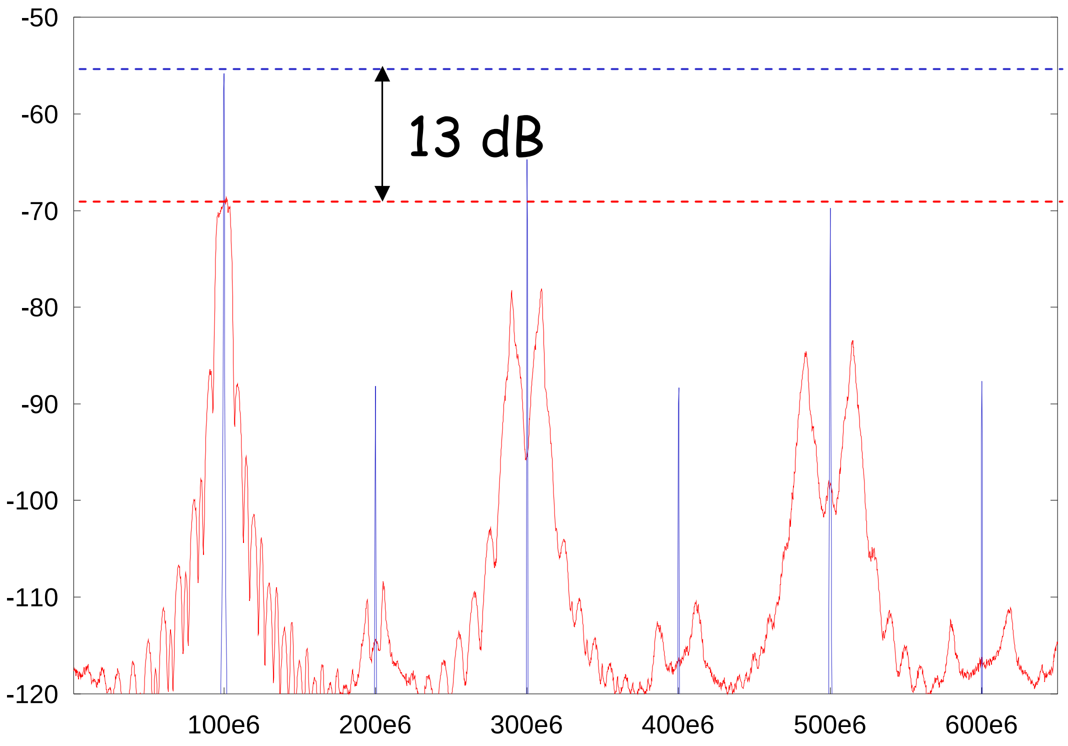
Circuit post-layout simulations

• Comparison between ***theoretical*** and ***simulated*** (from extracted netlist) power spectrum



Very good matching

Comparison between ***non-modulated*** (standard clock) and ***modulated*** (spread-spectrum clock) power spectrum



$$f_0 = 100MHz$$

$$\Delta f = 3.18MHz$$

$$m = 0.318$$

$$RBW = 120kHz$$

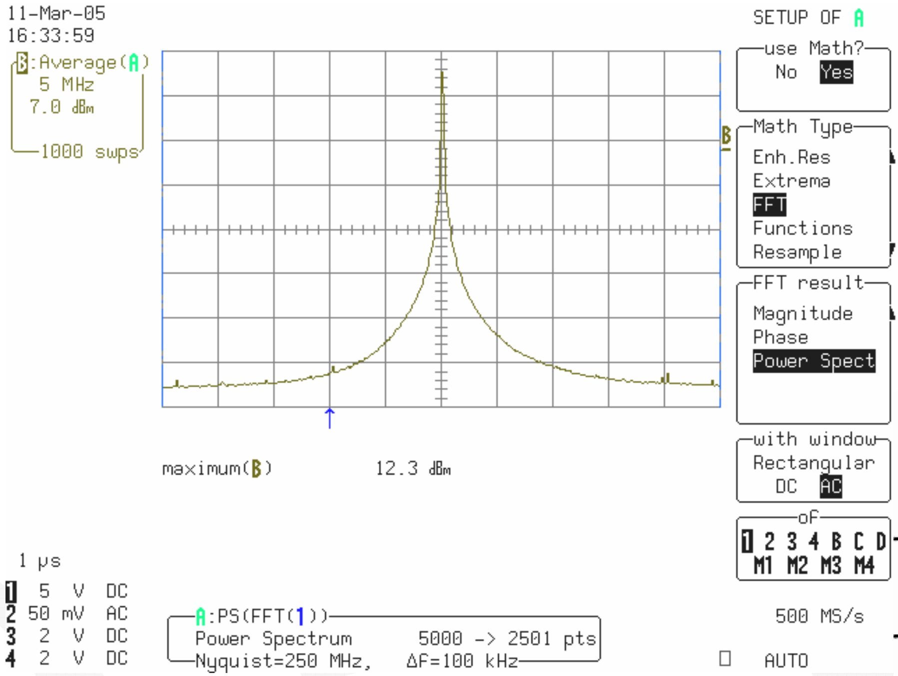
(as indicated by CISPR regulation)

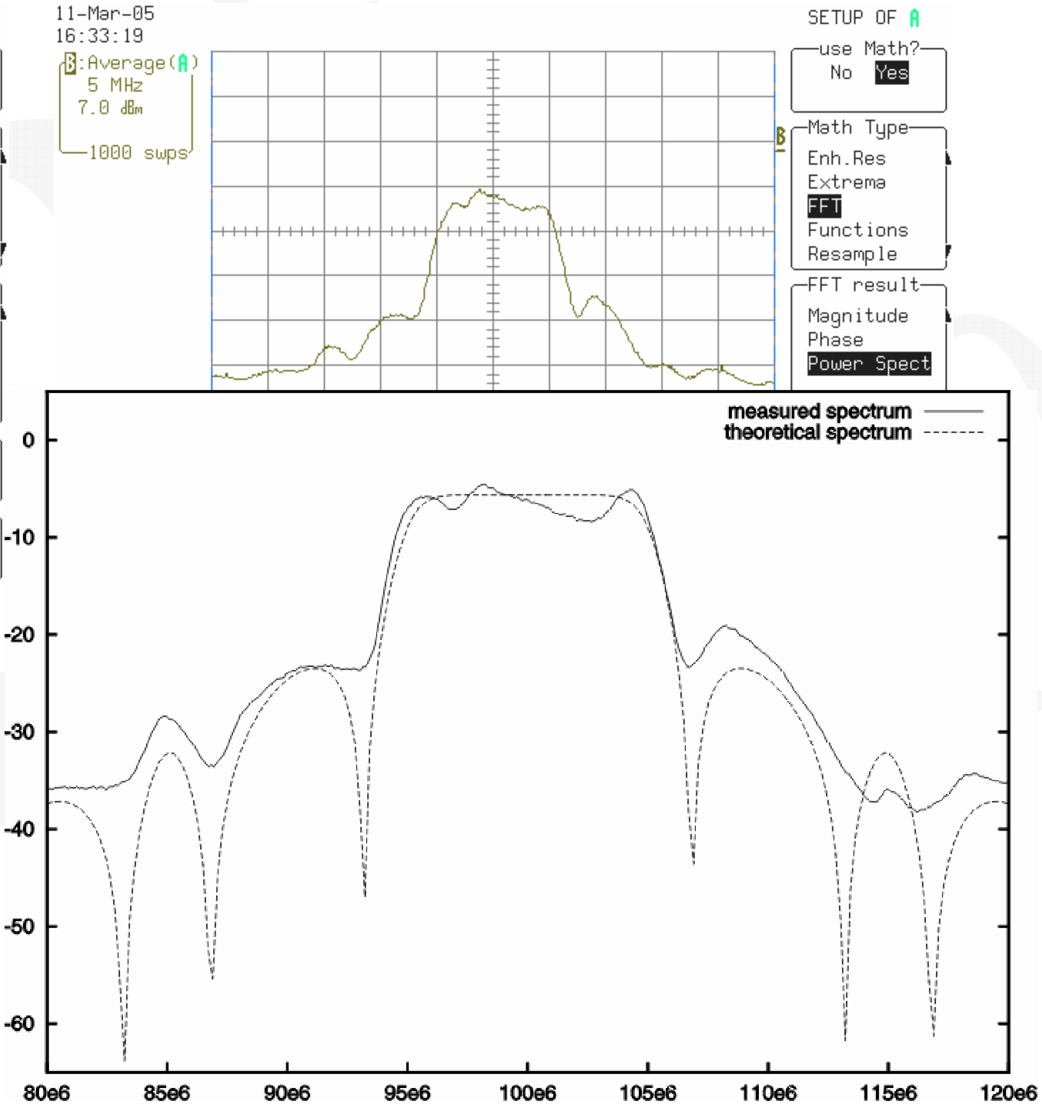
Peak reduction = 13dB

(on the fundamental tone)

Integrated spread-spectrum clock prototype

Comparison between ***non-modulated*** (standard clock) and ***modulated*** (spread-spectrum clock) power spectrum





$$f_0 = 100MHz$$

$$\Delta f = 3.18MHz$$

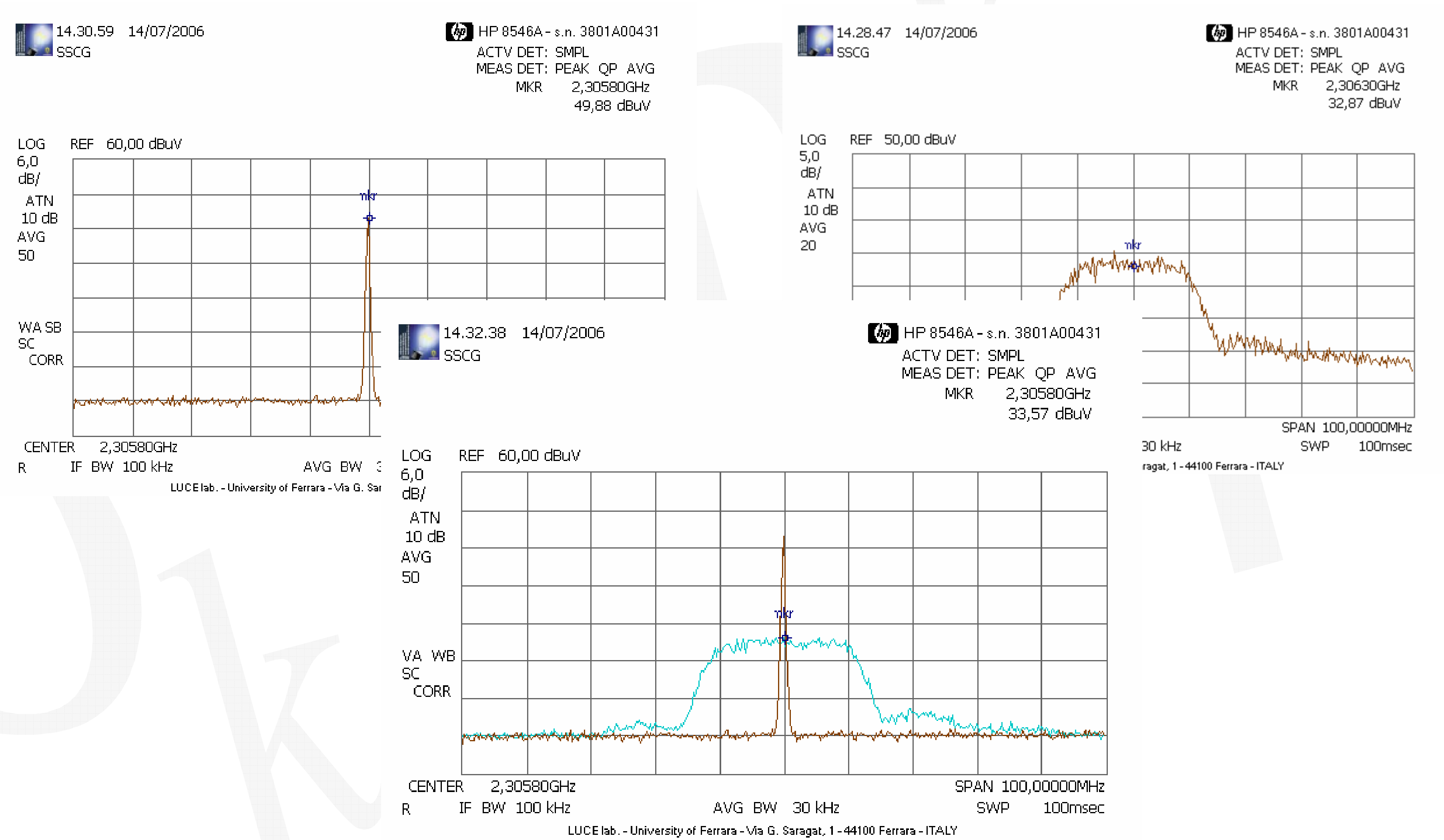
$$m = 0.318$$

Peak reduction = 17dB

(on the fundamental tone)

Does it work at hiher frequencies?

- New prototype of clock generator designed to work at in a tunable range between 2 and 2.5 GHz (UMC L180, 0.18µm, 1P6M)

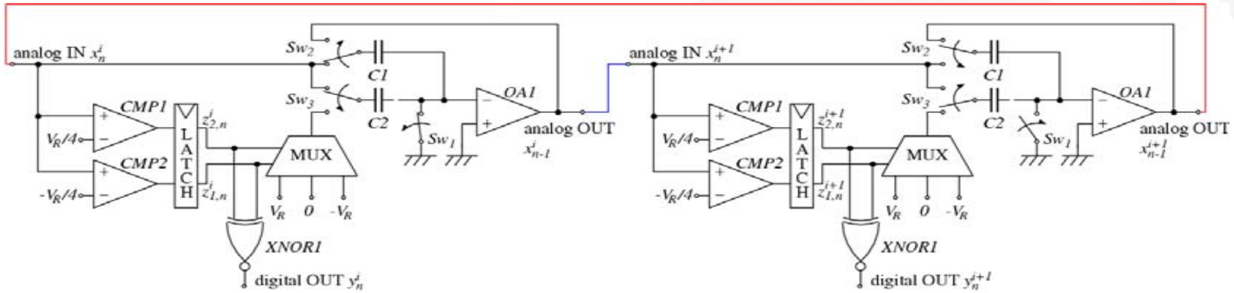


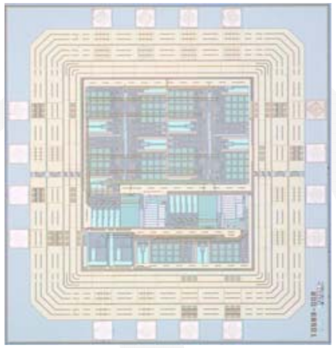
Conclusion -I

- Novel chaos-based methodology for EMI reduction in switching power converters and digital circuits and boards…
- … **shields need is reduced** so that cost and volume occupation are reduced senza introdurre schermi e quindi
- Low-EMI clock generator: **9dB EMI reduction** with respect to the best known and previously patented methods (used by IBM, Intel, Cypress). IC prototype working at 100MHz has been implemented and fully tested. Working frequencies can be increased.
- Current Feedback DC-DC converter: **22dB EMI reduction** with respect to the unperturbed case. Prototype realized with off-the-shelve components. Integrated version is a future step.
- Can be applied with all switching converters (also to drive motors)
- Future works: Application to SATA2 drivers (1.5GHz to 3GHz)

- Chaos-based generation of stochastic process with prescribed statistical features has been proved to give key advantages in:

➢ True Random Number Generation for Cryptographic Applications (Patent Pending)





– Implementation based on standard pipeline ADC structure ⇒ **extreme design reuse**

– Analytical proof that ideal system generates perfectly random bits (i.i.d.)

– Implementation in 0.35 AMS CMOS technology (3.3V supply, A=1480 um x 1620 um, fB = 40Mb/s (8-stages)) ⇒ **>100 times faster** than state of the art True-RNG

– Implementation **satisfy NIST test suites** (800-22, 140.2) and **DieHard**

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Measurements Results