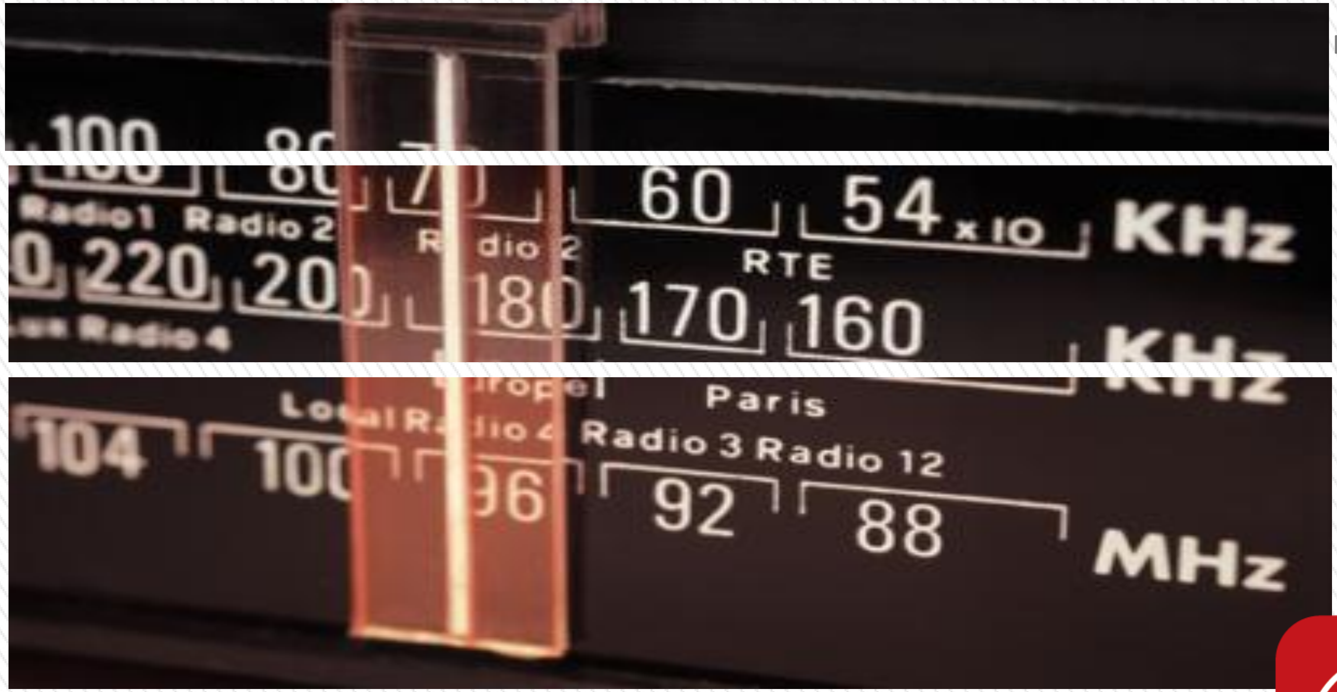

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RESEARCH | DEVELOPMENT| LEARNING

radio systems

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Wireless Power Transmission

Universidade de Aveiro Developments

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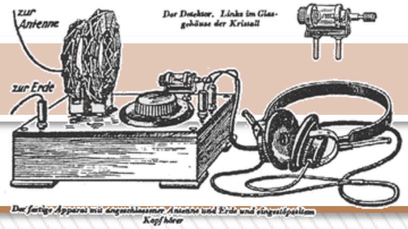
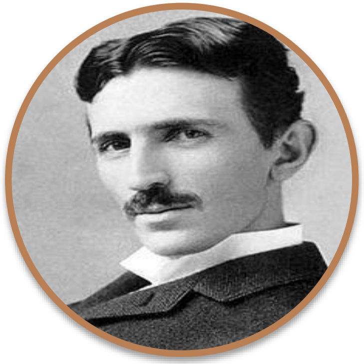
radio systems

History

Marconi was an Italian inventor. He is considered as the father of radio communication. He shared the 1909 Nobel Prize in Physics with Karl Ferdinand Braun "in recognition of their contributions to the development of wireless telegraphy".





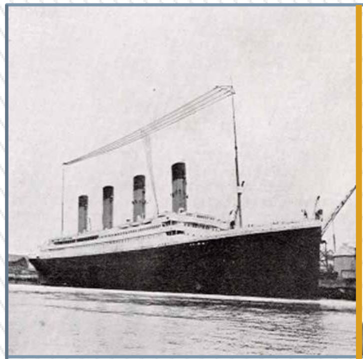
Tesla demonstrated wireless energy transfer to power electronic devices in 1891 and aspired to intercon-tinental wireless transmission of industrial power in his unfinished Wardenclyffe Tower project.

History


Music While Walking With Radio
LOUD SPEAKER


Mazarin Sings by Wireless
"Carmen" Heard a Mile Off
2-25-1910

Evolution of Radio Communications



Marconi Radio
Long-distance Communications

Broadcast Radio

Communications for the Masses

Television

High Social Impact

Mobile Phones

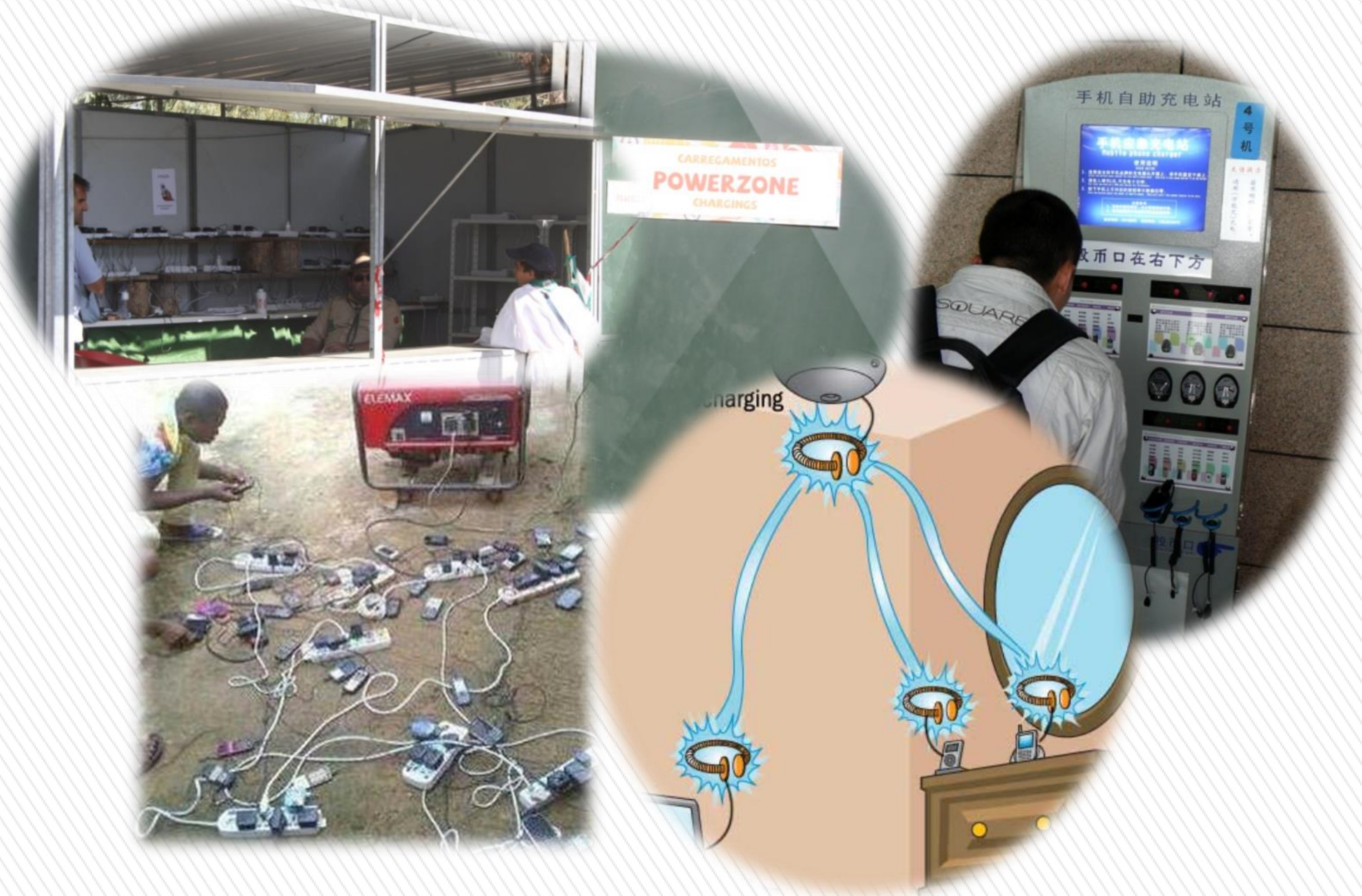
Mimicking God Omnipresence

Data Communications

Interconnecting people

Evolution of Radio Energy Needs

Basic Needs: Water → Food → Energy



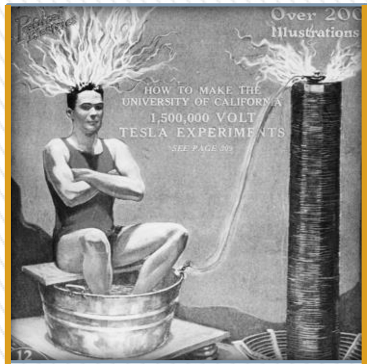
Battery Elimination

➢ Batteries take **hundreds of years to decompose**, posing a serious threat to the public health and to the environment.

- Considering 4 Million habitual residences in Portugal (INE – Censos 2011) and assuming that:
  - ✓ 75% of them have a TV equipment
  - ✓ 40% have a cable TV Box
  - ✓ 30% have a Sound System

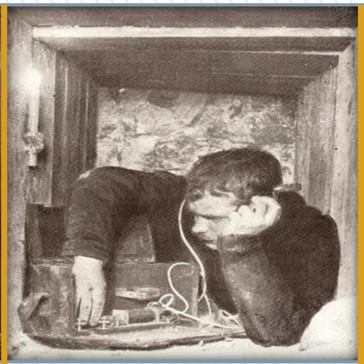
- We end up with an average of **5.8 Millions of remotes in Portugal**
- Assuming two batteries per remote and two battery changes per year we have a **total of 23.2 Millions batteries being wasted every year !!**

Evolution of Radio Power Transmission



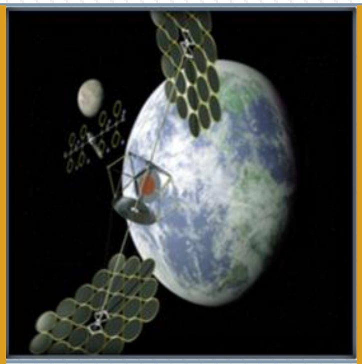
Initial Discovery

Power been transmitted via air !!



Crystal Radios

Original made with Galena



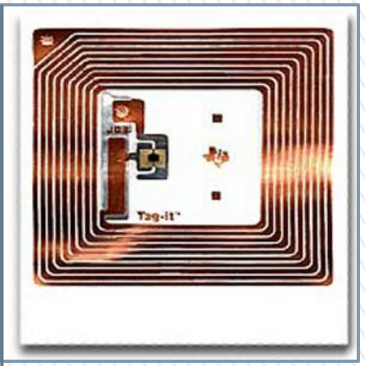
Satellite Proposals

Power collected in Space and sent to ground via microwaves

Rectenas

Antennas that collect energy

William Brown 1964



RFID

Powering up small Tags's

Next Frontier Wireless Things

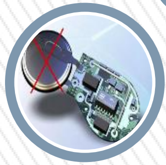
Low bit Rate

- Low Power
- Low complexity

High bit Rate

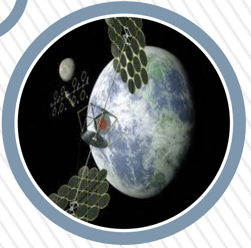
- High Power
- High complexity

Next Frontier



Battery-less Sensors for health applications

Car Energy Collector



High Efficient Energy Collection

RFID's

Domestic Appliances Wireless Energized

Agriculture passive sensors

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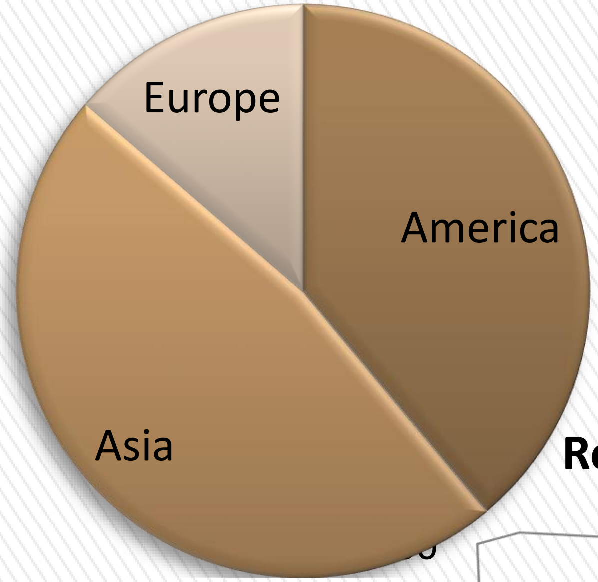
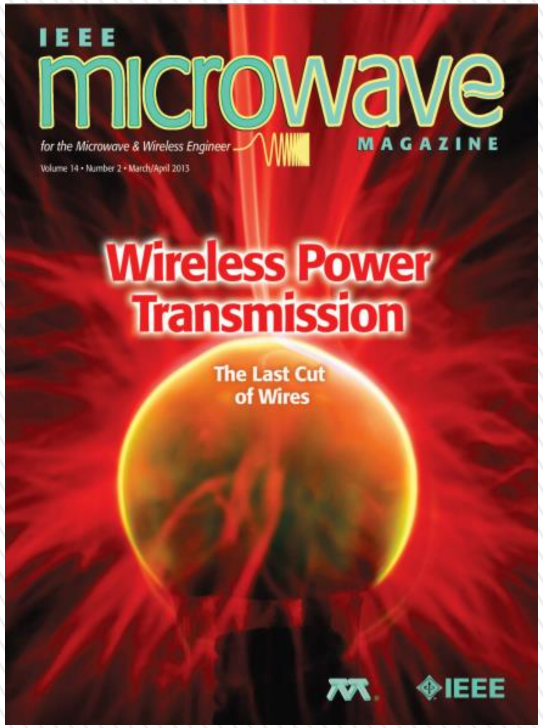
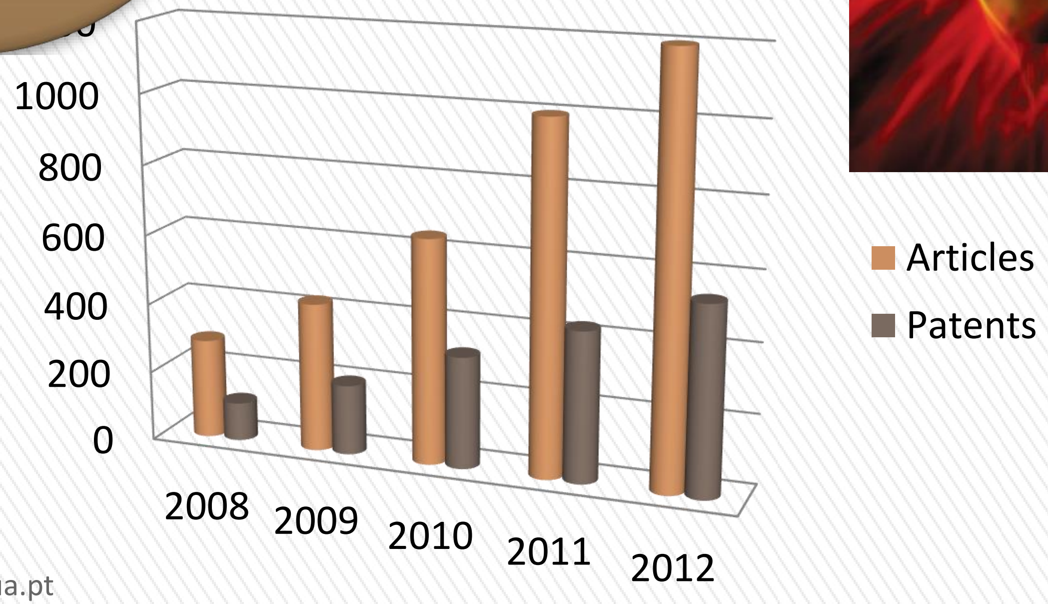
Next Frontier European Perspective





WIPE
COST IC1301

Research Statistics on WPT



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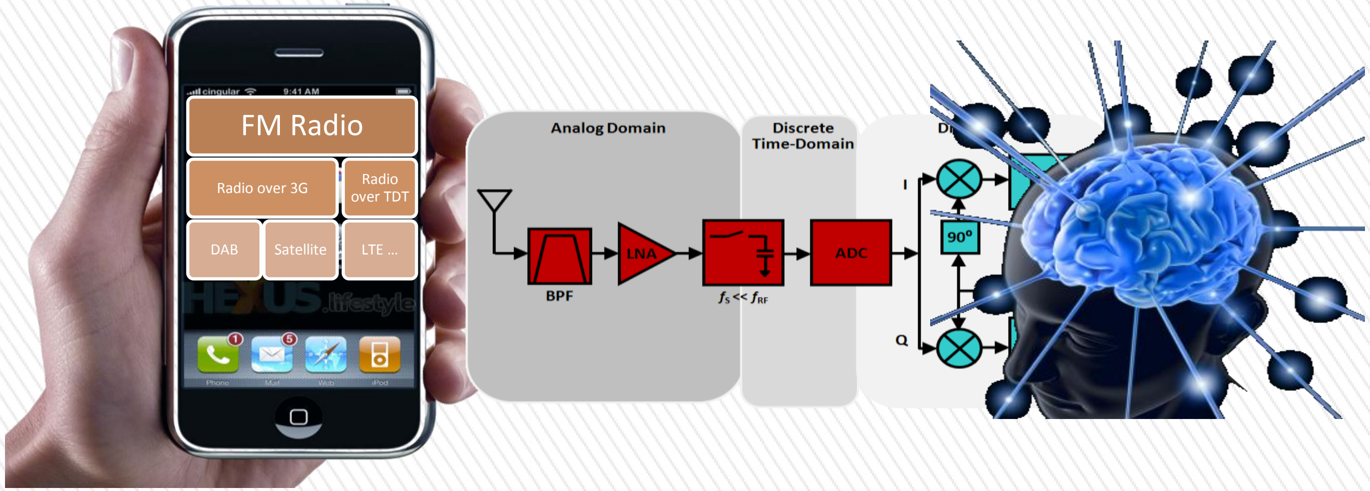
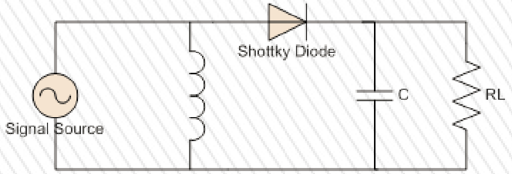
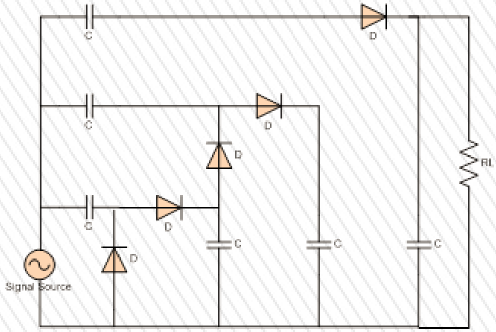
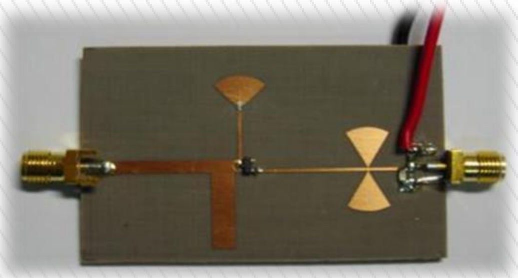
Challenges Technology developments





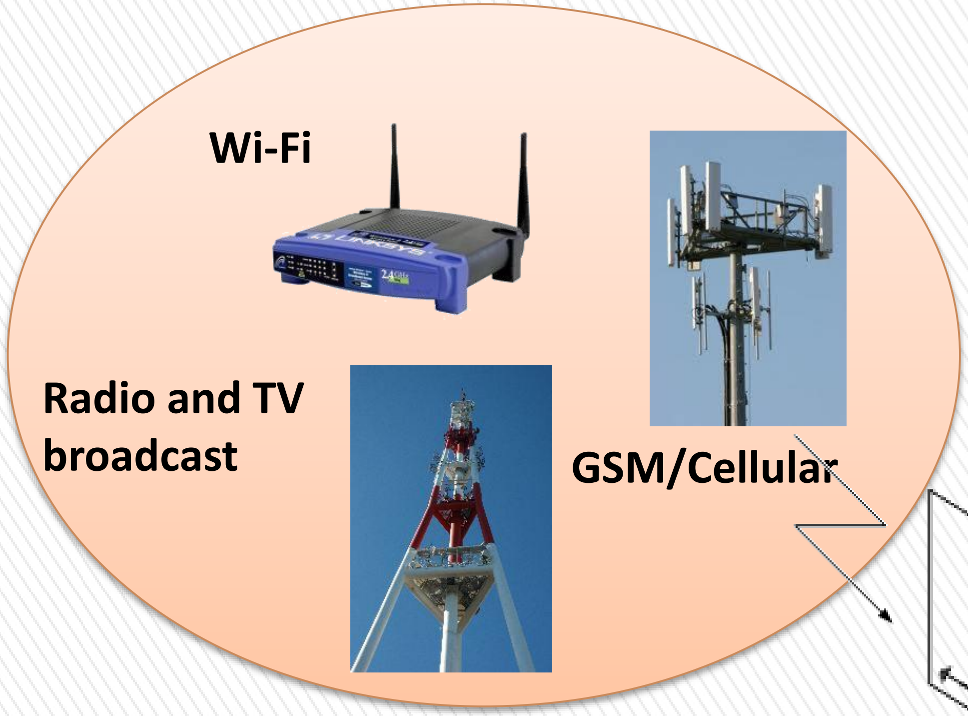




E. Harvesting and WPT

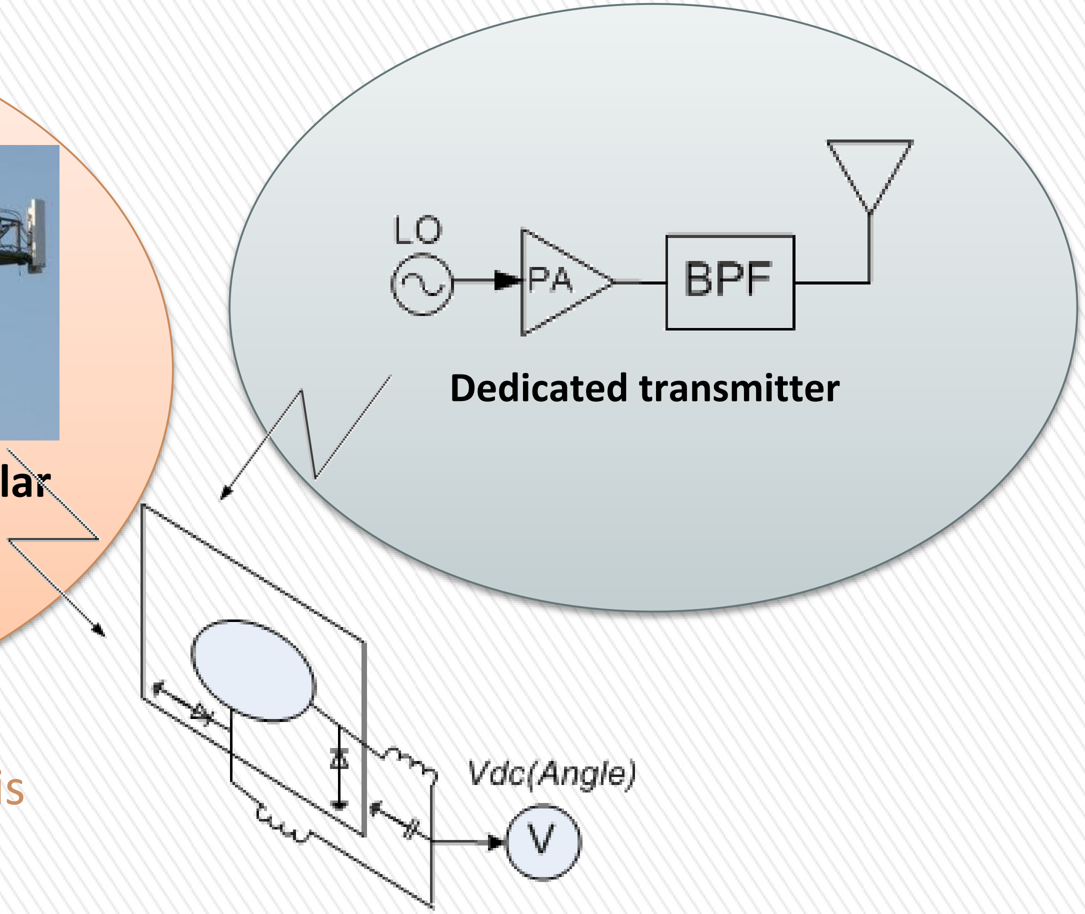
Energy Harvesting

Ambient Electromagnetic Energy



Wireless Power Transmission (WPT)

Dedicated and known Transmitter



Rectenna = antenna + rectifier

In both cases: Received RF energy is converted into DC power

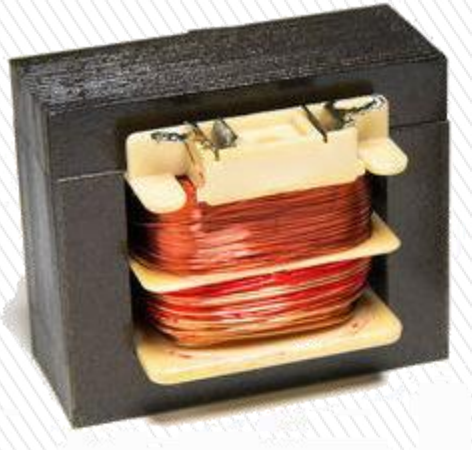
Wireless Transmitted Energy

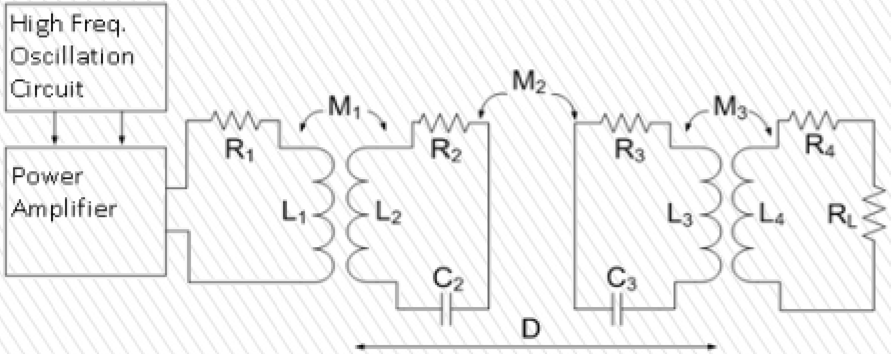
How it Works

Inductive Power Transmission

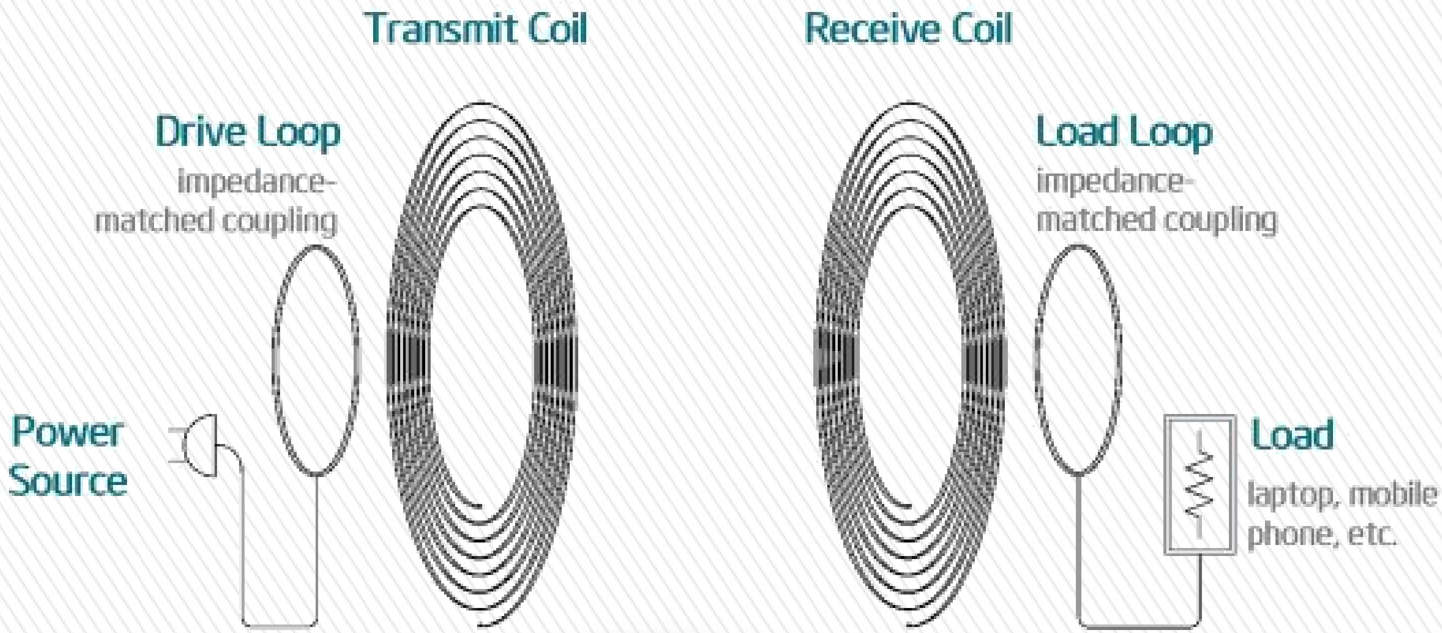
Inductive Power Transmission is high efficient at very close ranges

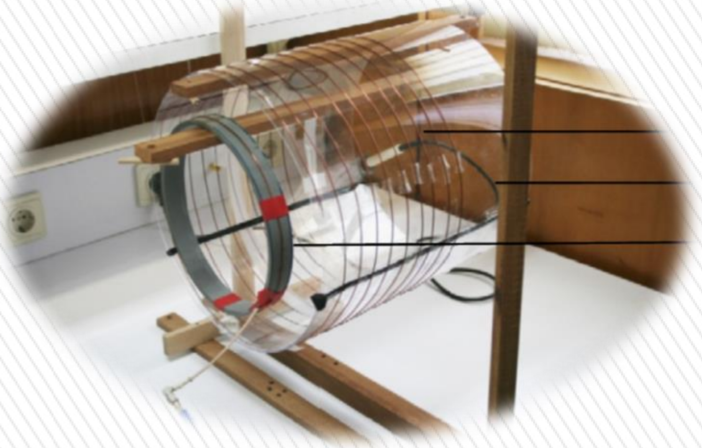
Working principle similar to Transformers





Resonant Power Transmission

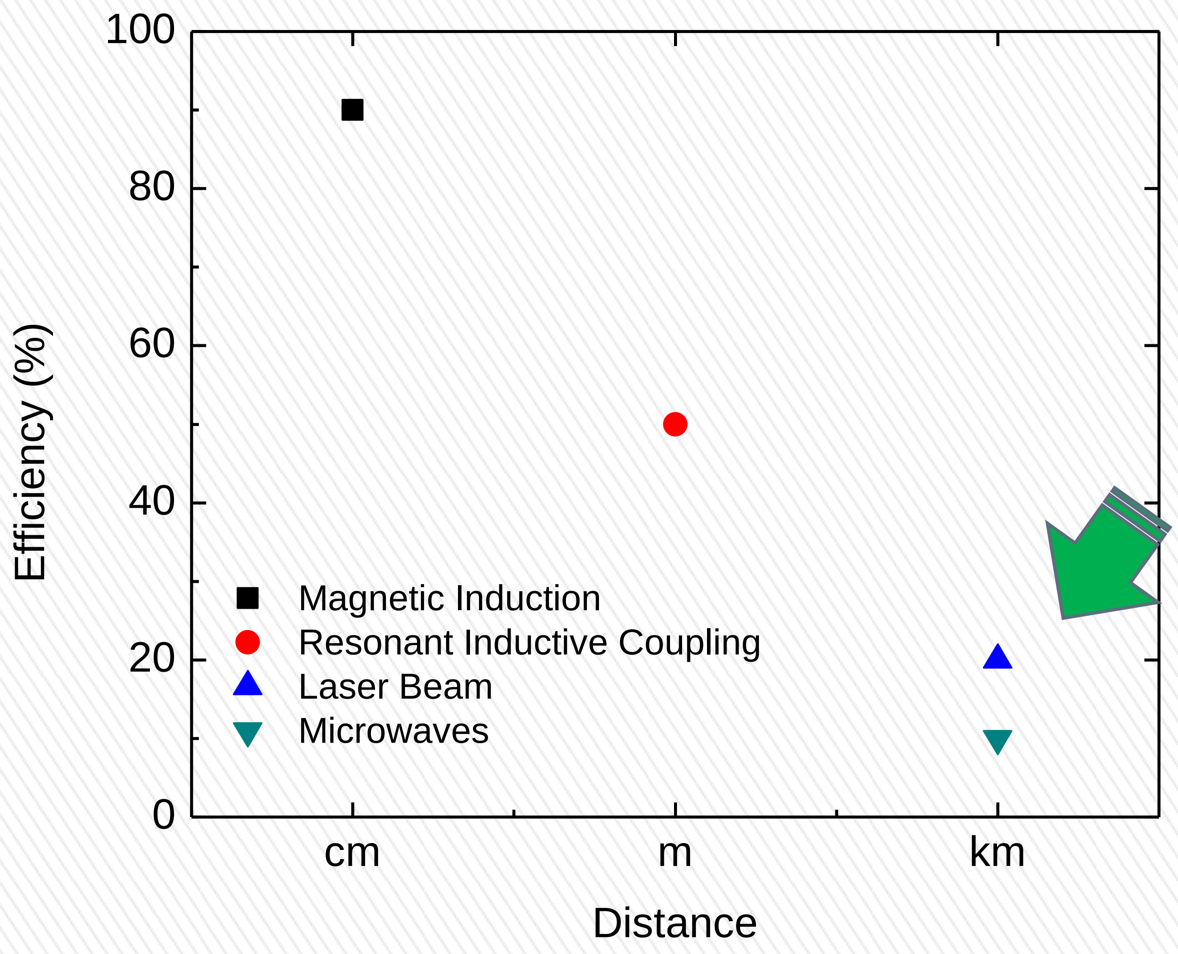




Resonant Power Transmission achieves long ranges …

N. Bonifácio; André, P.S e Nuno Borges Carvalho; "Resonant Wireless Power Transmission" - Chapter in Advances in Energy Research – Vol. 8, Edited by: Morena V. Acosta, Nova Publisher, New York, 2011.

Radio Power Transmission



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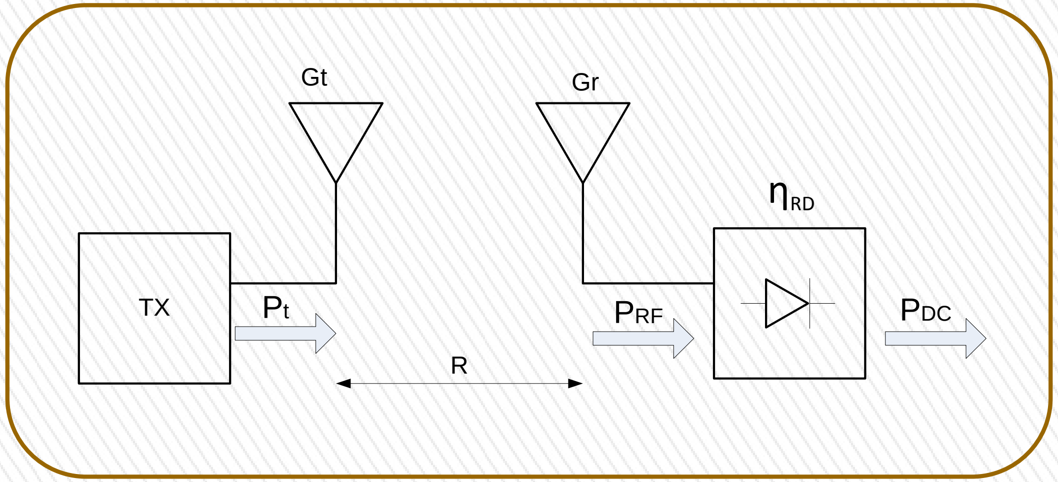
How to Transmit Power via Wireless



$$P_{DC} = \eta_{RD} P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{R^n}$$

Increase P_{DC}

I. Increase transmitted Power

II. Increase antenna gains G_t and G_r

III. Increase RF-DC Efficiency

RF-DC Efficiency is given by: $\eta_{RD} = \dfrac{P_{DC}}{P_{RF_{Average}}}$

RF-DC Efficiency can be increased by designing improved RF circuits

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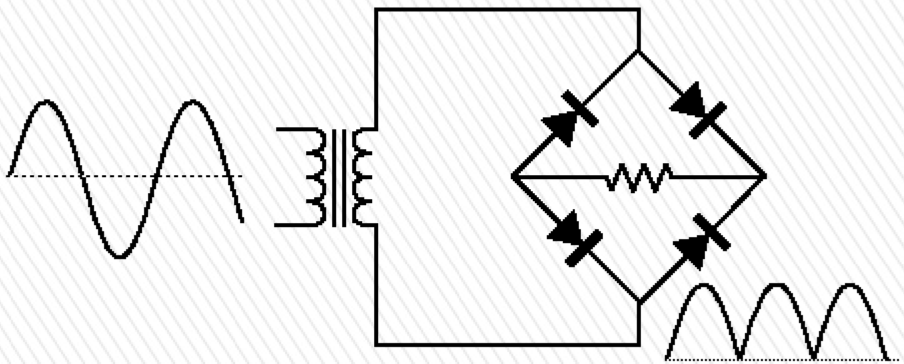
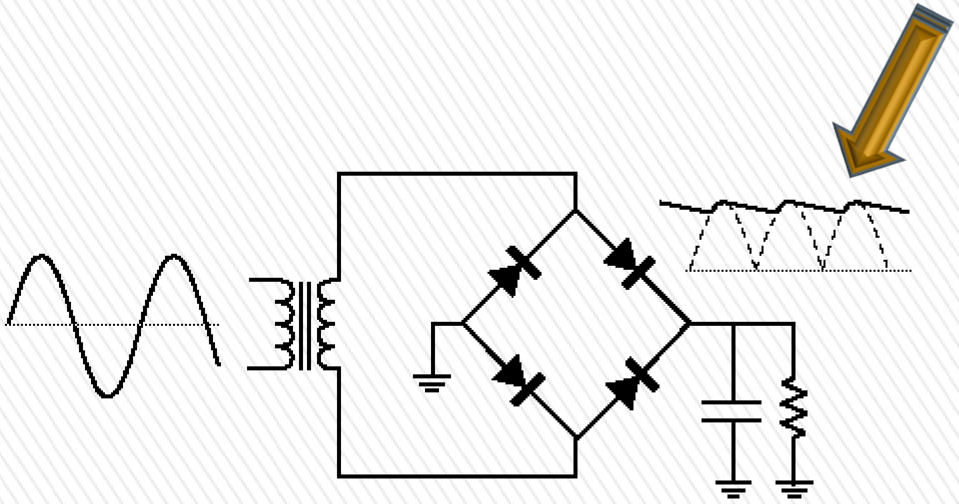
How to Convert RF Energy to DC Power



Diode rectify a sine-wave

An output filter extracts the DC waveform …



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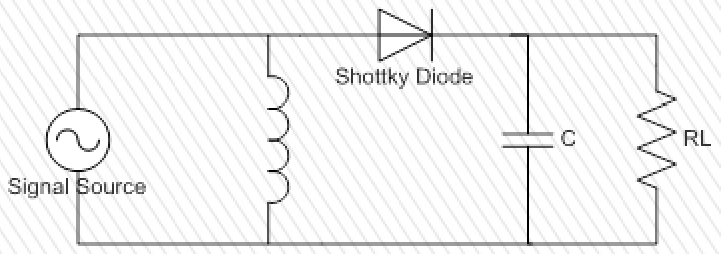
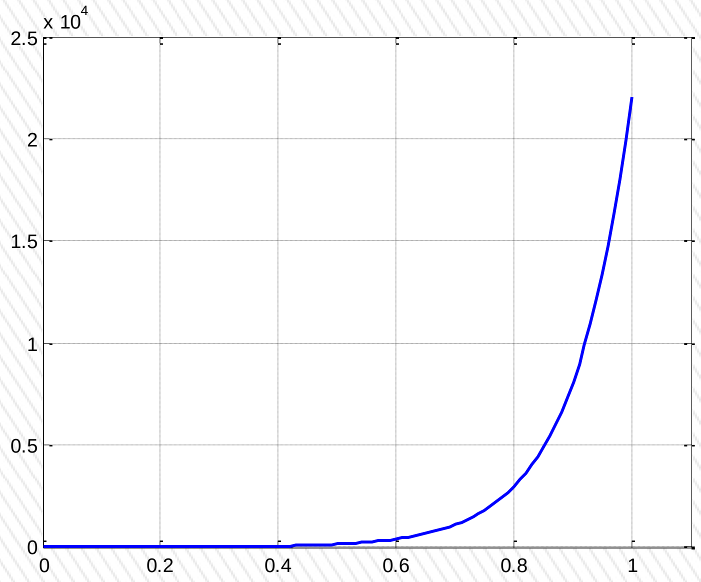
How to Convert RF Energy to DC Power

Single diode detector



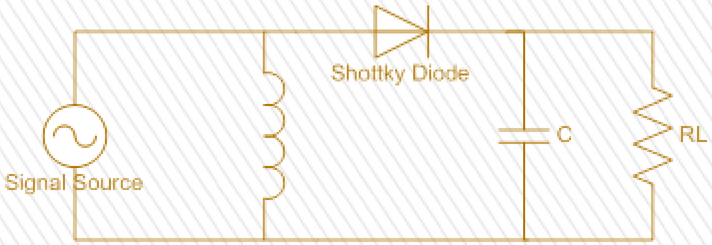


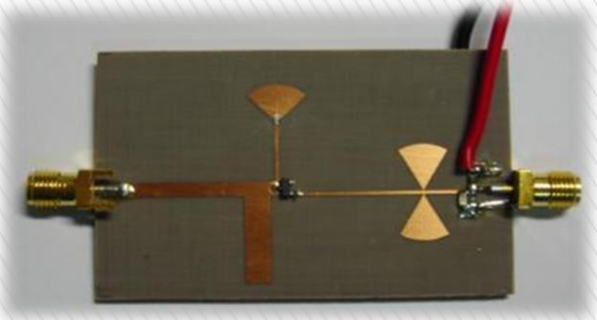
$$y(t) = I_s\left(e^{\frac{V}{V_T}} - 1\right) \approx k_1 v(t) + k_2 v(t)^2 + \cdots$$

$$y(t) \approx k_1 A\sin(\omega t) + k_2\left[A\sin(\omega t)\right]^2 = k_1 A\sin(\omega t) + k_2\frac{A^2}{2}\left[\sin(2\omega t) + 1\right]$$

How to Convert RF Energy to DC Power

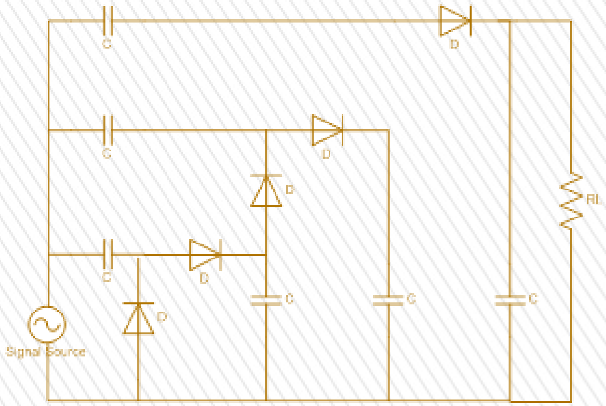
Single diode detector

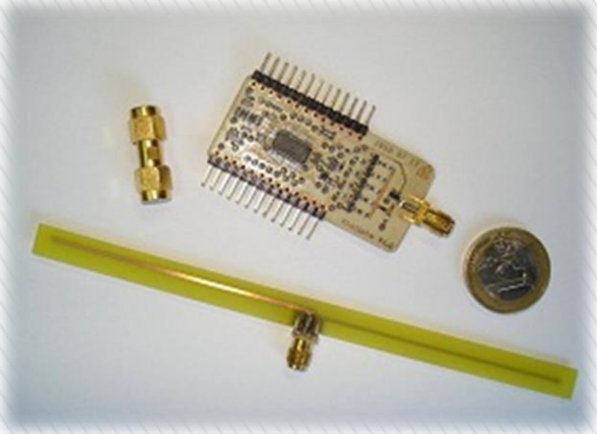




$$v_{DC}(t) \approx k_2 \frac{A^2}{2} \propto P_{in}$$

N-level Voltage Multiplier

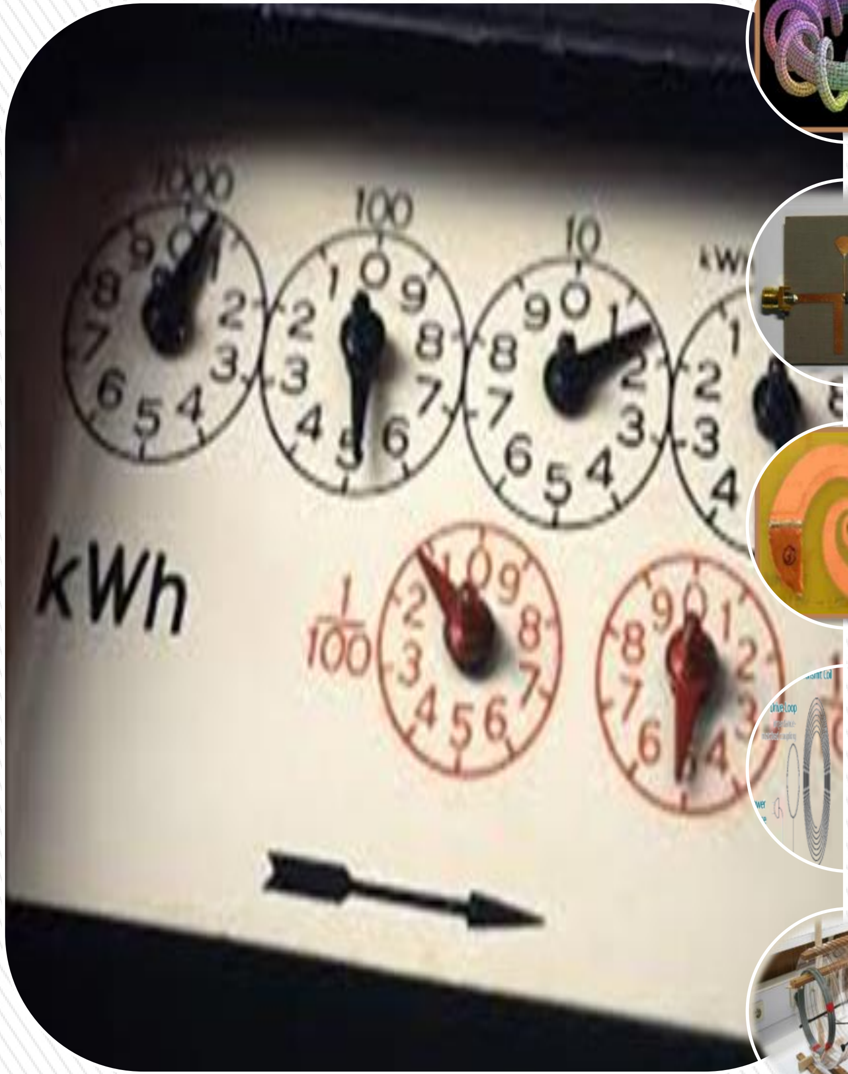




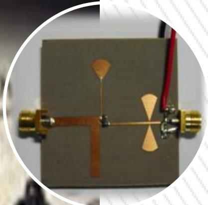
For RF circuits, input matching and output matching is more complex to dealt with, and thus several areas should be explored.

Research Approaches

Increase overall DC-DC efficiency

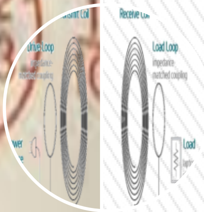


Modeling



Increase
RF-DC
Efficiency

Improve
Antenna
Design



Reduce Losses
in Inductors

Align strategies
for commercial
systems

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R&D Approaches…

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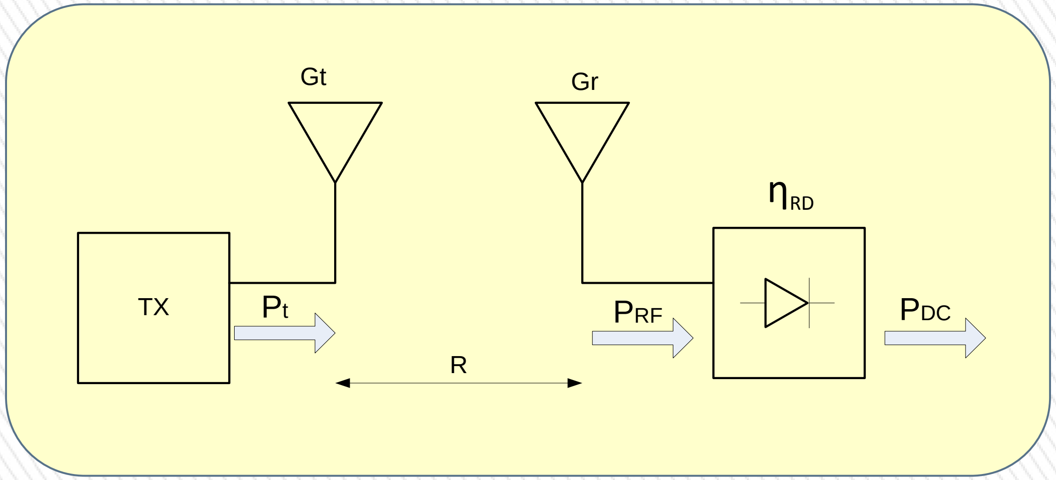
Extend the Coverage Range …

Use of Multi-sines in Circuit Design

- » Maximizing the WPT Efficiency is a complex matter
- » Maximum range is imposed by the forward link
- » RF-DC efficiency plays a key role



$$P_{DC} = \eta_{RD} P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{R^n}$$

Increase P_{DC}

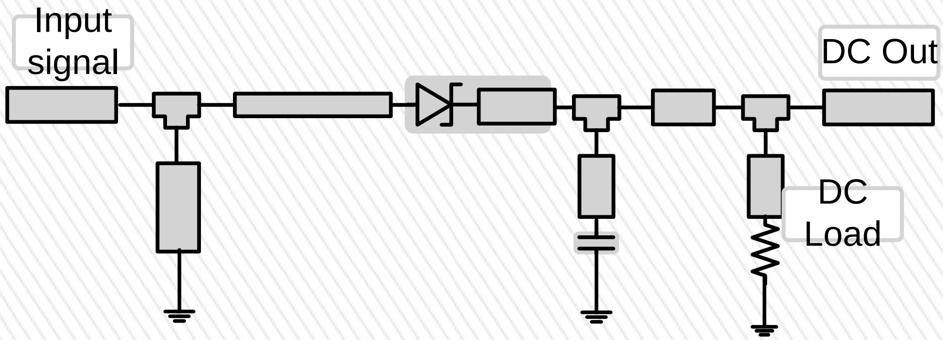
I. Increase transmitted Power

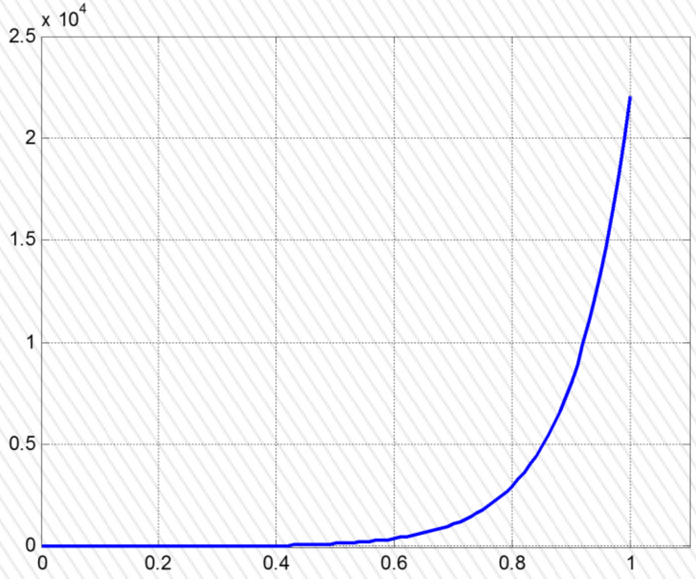
II. Increase antenna gains G_t and G_r

III. Increase RF-DC Efficiency

Use of Multi-sines in Circuit Design

» RF-DC converters are most of the time based on a Schottky diode





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$$y(t) \approx k_1 A\sin(\omega t) + k_2[A\sin(\omega t)]^2 = k_1 A\sin(\omega t) + k_2\frac{A^2}{2}[\sin(2\omega t)+1]$$

Use of Multi-sines in Circuit Design

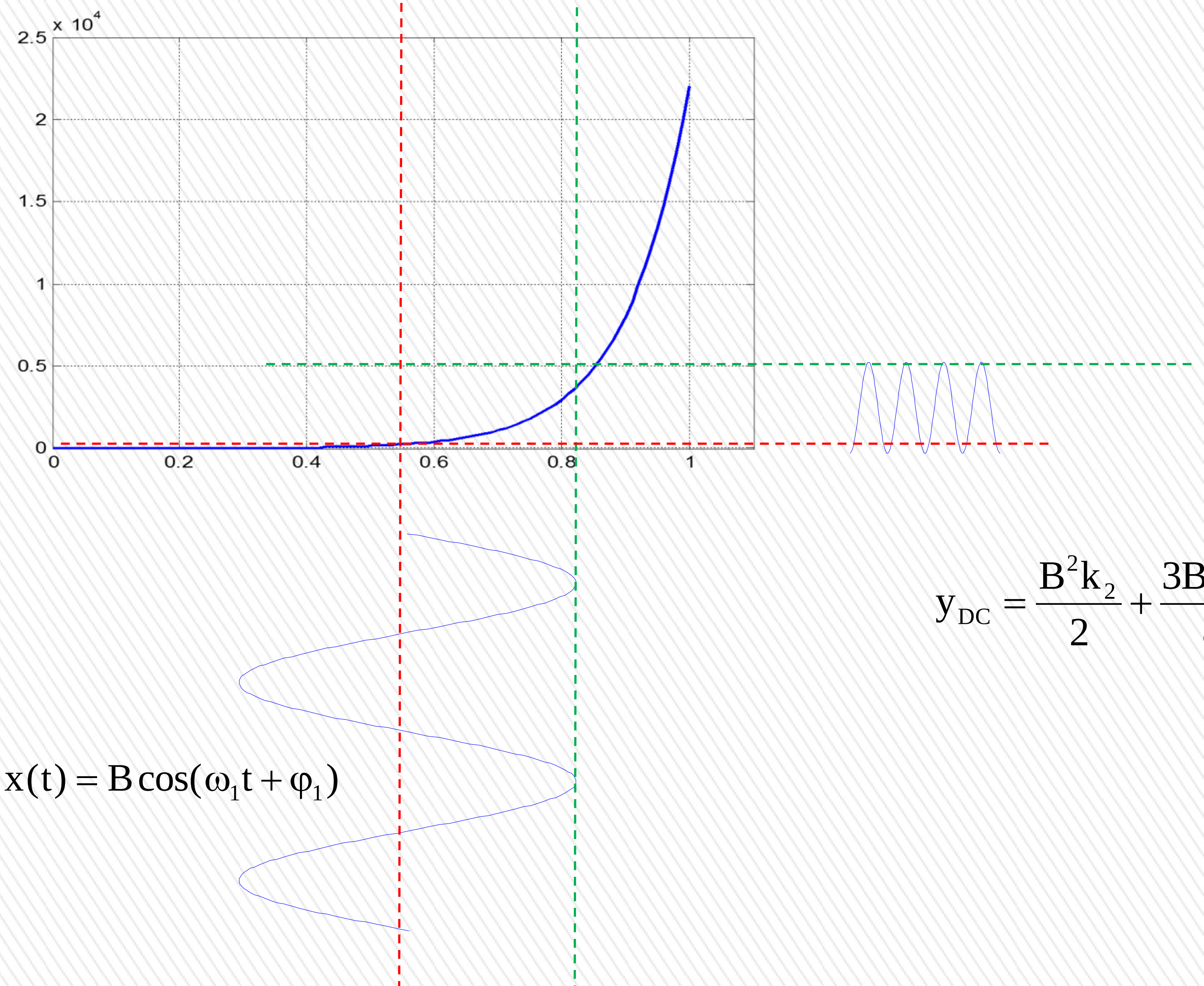
- ❑ Schottky diode model approximated by a polynomial series expansion

$$I_D = I_S\left(e^{\frac{V_b}{nV_t}} - 1\right) \Rightarrow y(t) = \sum_{n=0}^{N} k_n \cdot x(t)^n \Rightarrow y(t) = k_2 x(t)^2 + k_4 x(t)^4$$

- ❑ single tone excitation of the diode

$$\mathrm{x(t) = B\cos(\omega_1 t + \varphi_1)} \qquad \mathrm{y_{DC} = \frac{B^2 k_2}{2} + \frac{3B^4 k_4}{8}}$$

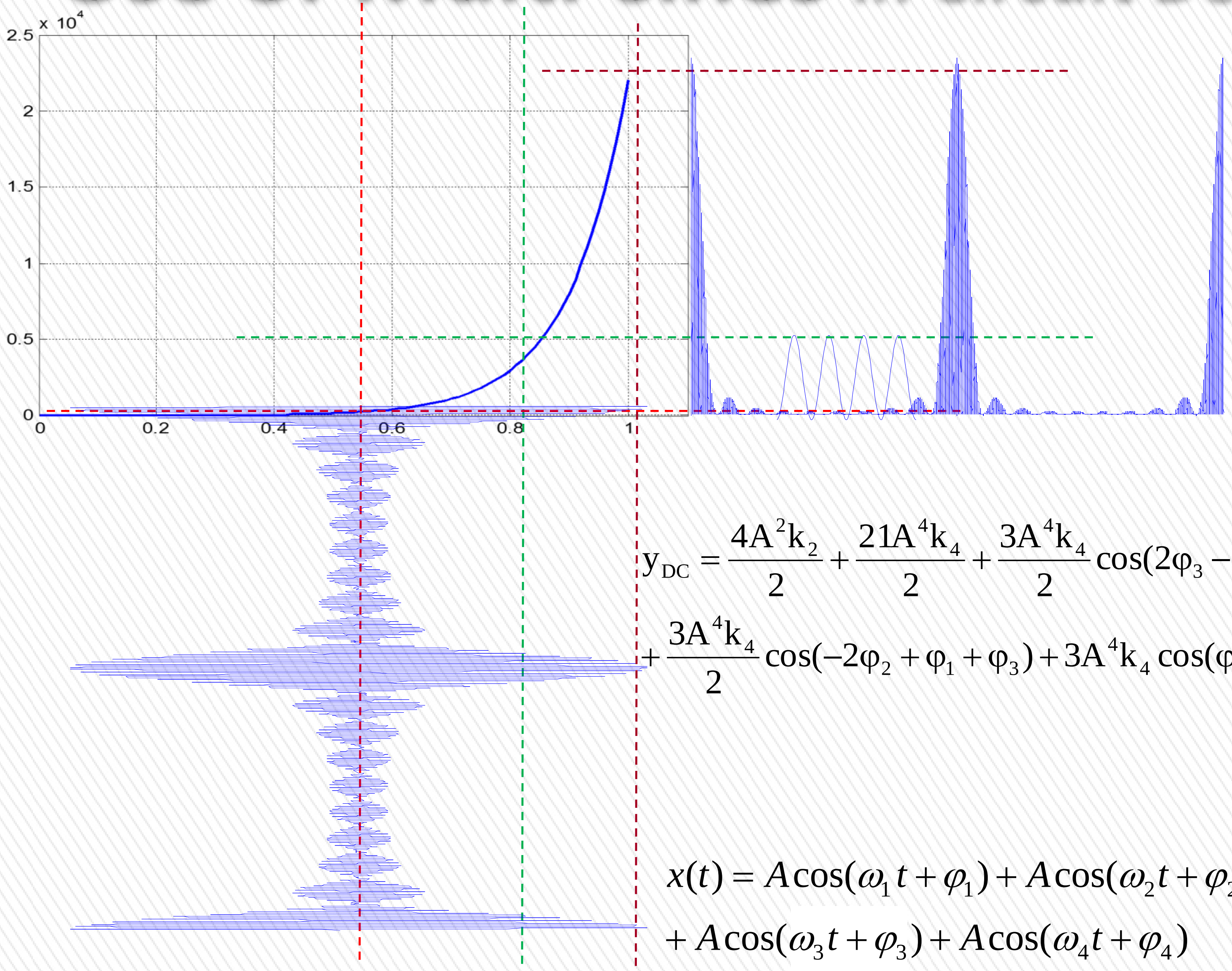
Use of Multi-sines in Circuit Design



$$y_{DC} = \frac{B^2 k_2}{2} + \frac{3B^4 k_4}{8}$$

$$x(t) = B\cos(\omega_1 t + \varphi_1)$$

Use of Multi-sines in Circuit Design



$$y_{DC} = \frac{4A^2k_2}{2} + \frac{21A^4k_4}{2} + \frac{3A^4k_4}{2}\cos(2\varphi_3 - \varphi_2 - \varphi_4)$$

$$+\frac{3A^4k_4}{2}\cos(-2\varphi_2 + \varphi_1 + \varphi_3) + 3A^4k_4\cos(\varphi_1 - \varphi_2 - \varphi_3 + \varphi_4)$$

$$x(t) = A\cos(\omega_1 t + \varphi_1) + A\cos(\omega_2 t + \varphi_2) +$$

$$+ A\cos(\omega_3 t + \varphi_3) + A\cos(\omega_4 t + \varphi_4)$$

Use of Multi-sines in Circuit Design

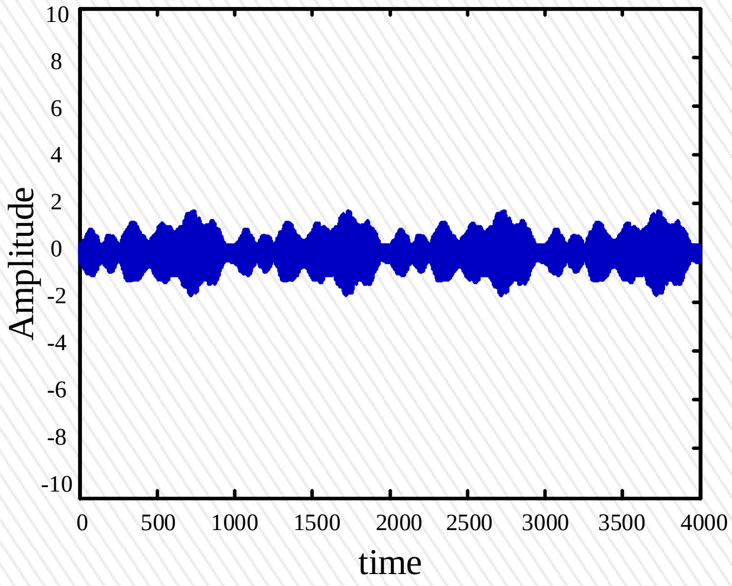
- multisine excitation of the diode

$$x(t) = A\cos(\omega_1 t + \varphi_1) + A\cos(\omega_2 t + \varphi_2) + A\cos(\omega_3 t + \varphi_3) + A\cos(\omega_4 t + \varphi_4)$$

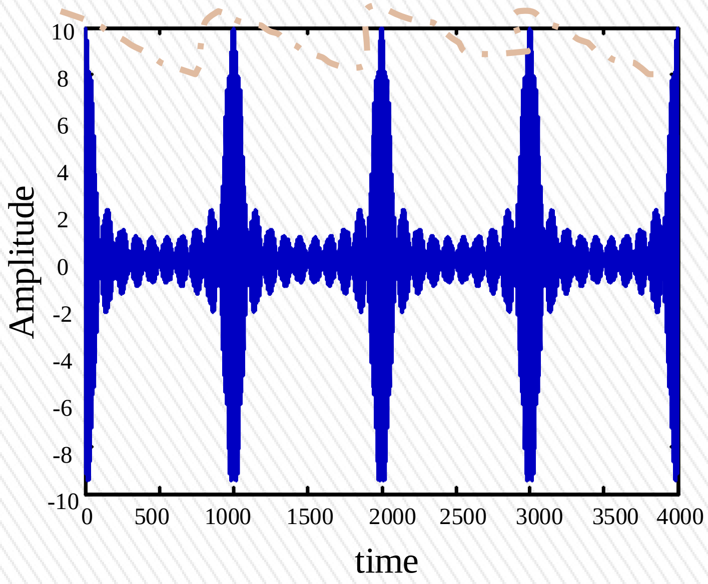
$$y_{DC} = \frac{4A^2 k_2}{2} + \frac{21A^4 k_4}{2} + \frac{3A^4 k_4}{2}\cos(2\varphi_3 - \varphi_2 - \varphi_4)$$
$$+ \frac{3A^4 k_4}{2}\cos(-2\varphi_2 + \varphi_1 + \varphi_3) + 3A^4 k_4 \cos(\varphi_1 - \varphi_2 - \varphi_3 + \varphi_4)$$

DC output depends on the phases!!

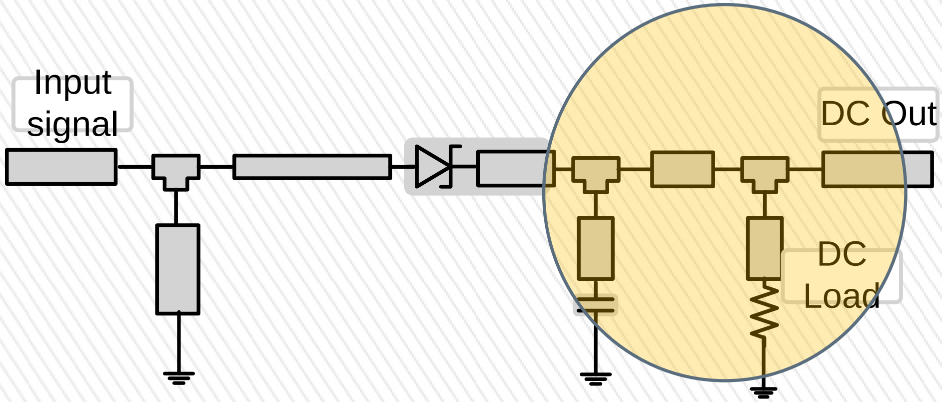
Use of Multi-sines in Circuit Design

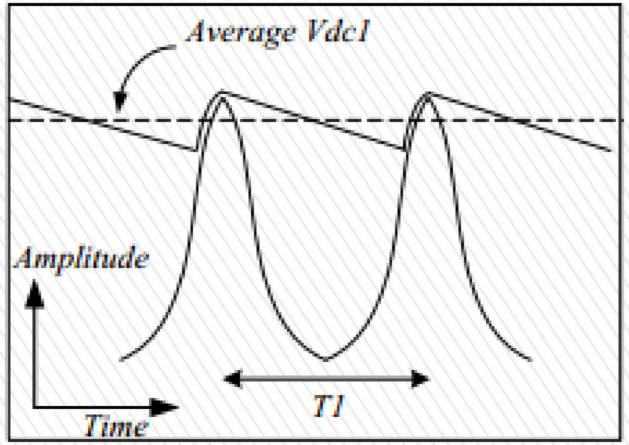


10 Tones of Randomized Phase



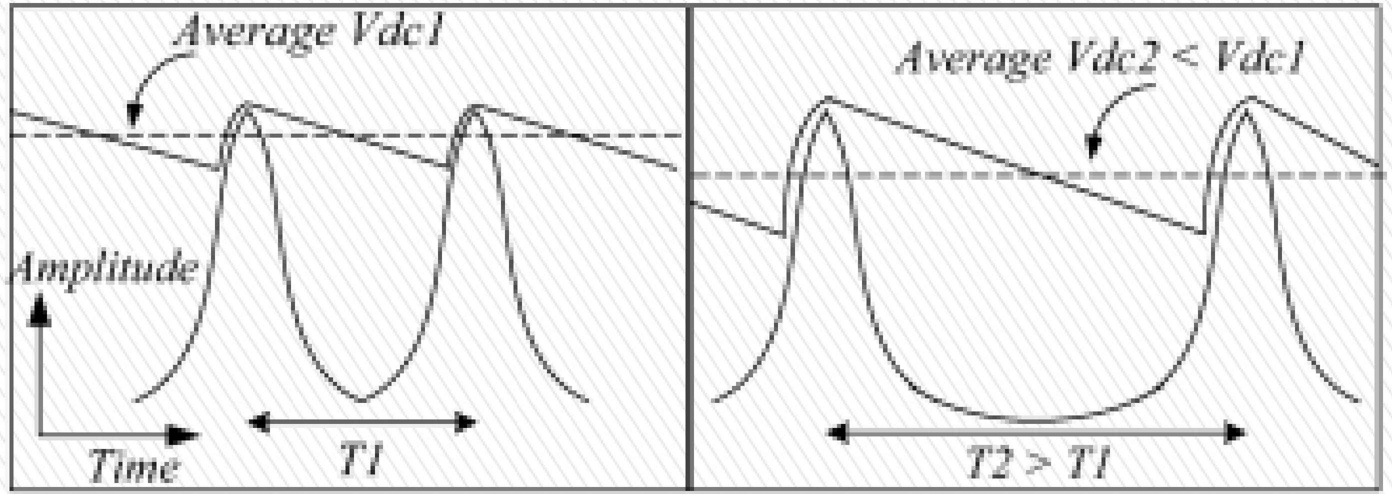
10 Tones of Equal Phase





(a)

Use of Multi-sines in Circuit Design



Tone separation is an important aspect to account for

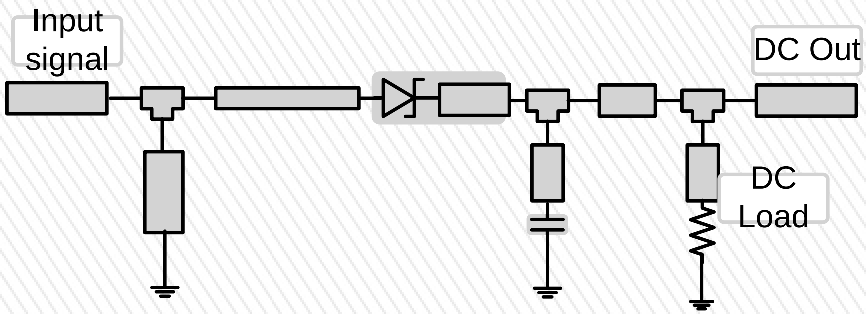
The lower the tone separation frequency, the higher time between peak voltage repetition

Use of Multi-sines in Circuit Design

» Two different circuits were built and tested:

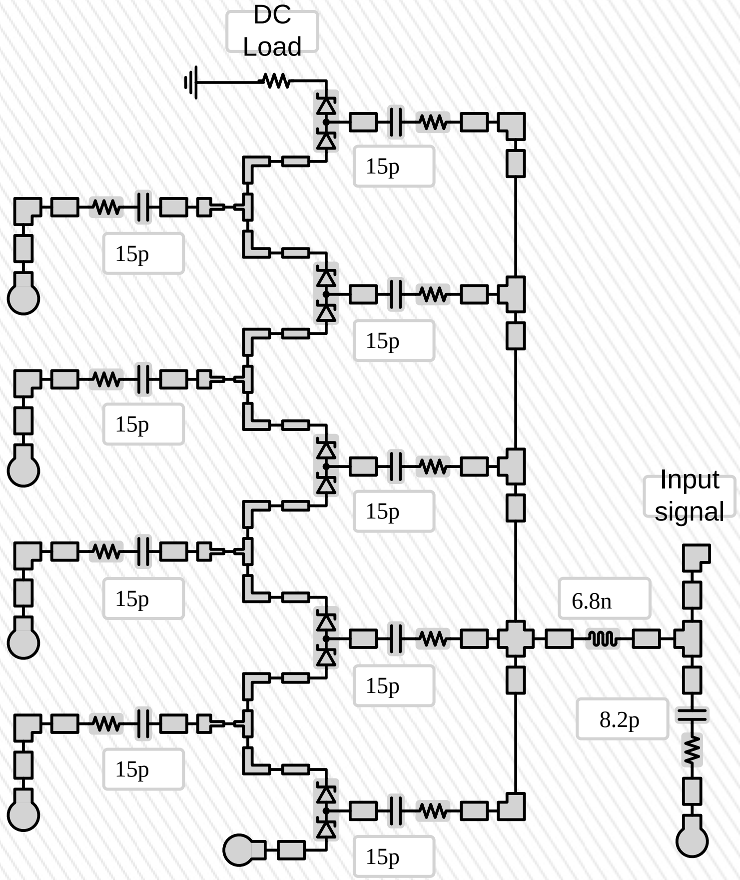
A single diode detector at 2.4GHz

(typically used in energy harvesting)



A charge pump at 866MHz

(typically used in RFID Tags)



Use of Multi-sines in Circuit Design

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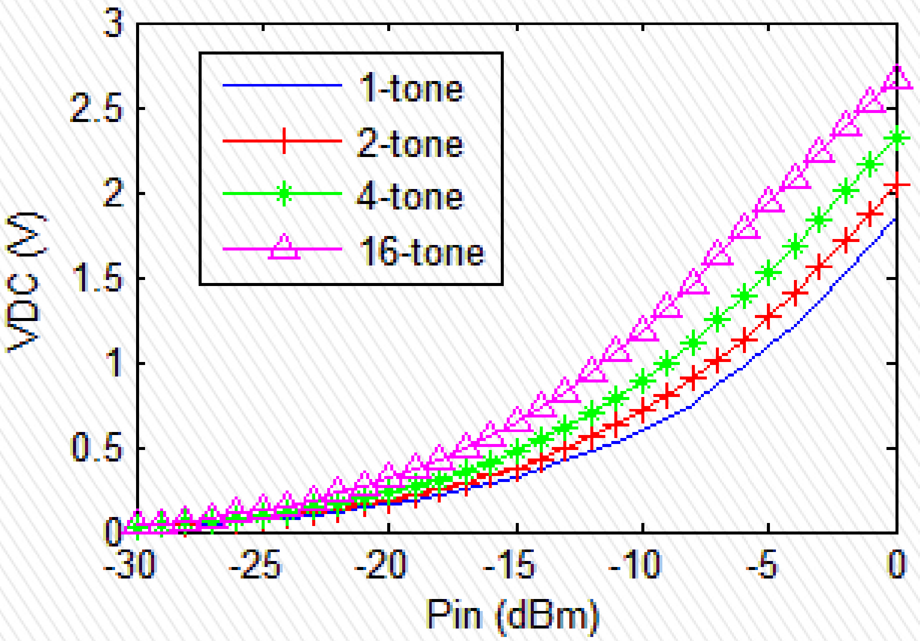
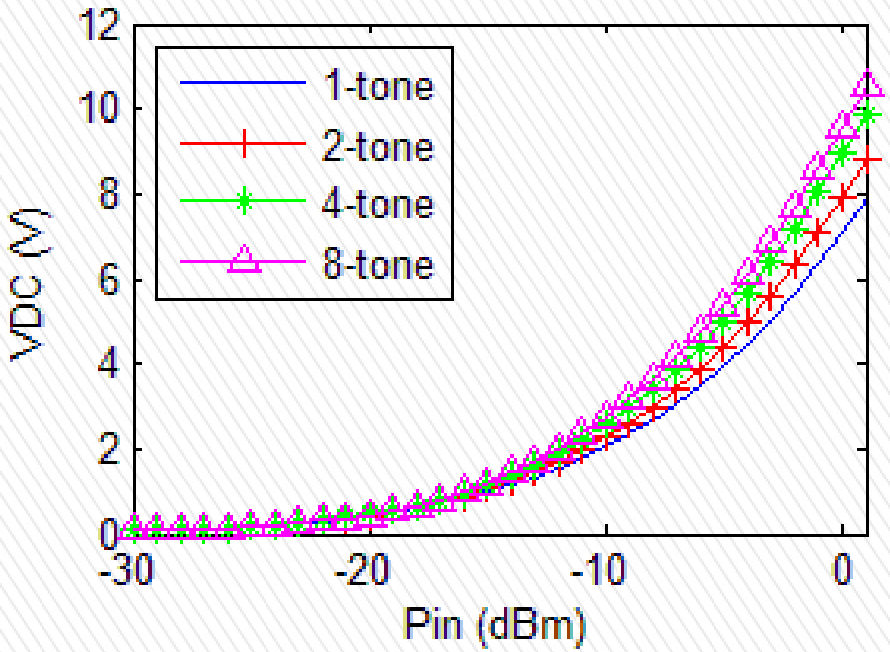
A single diode detector at 2.4GHz



A charge pump at 866MHz

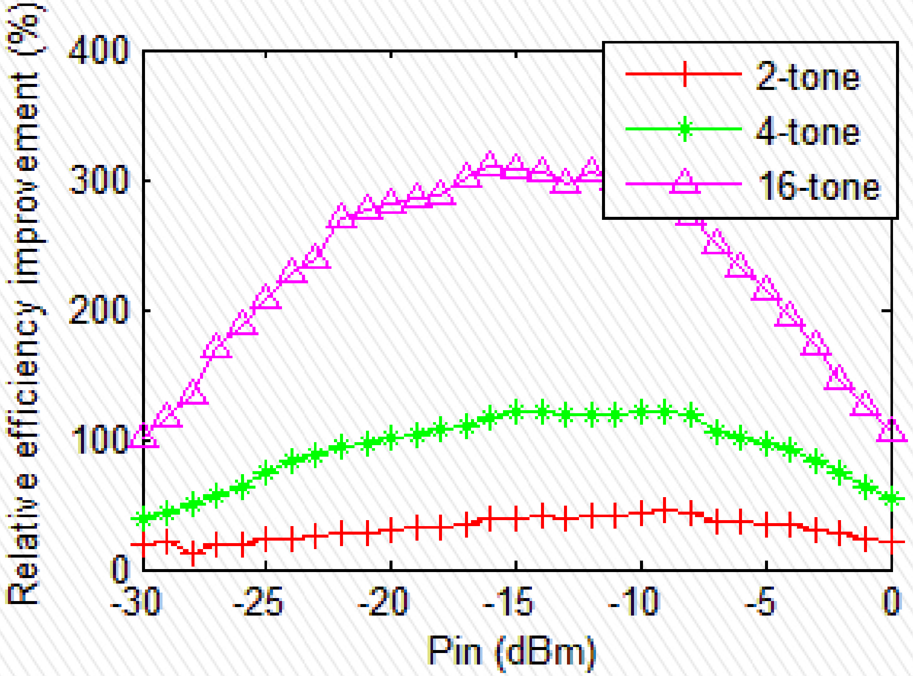


Use of Multi-sines in Circuit Design

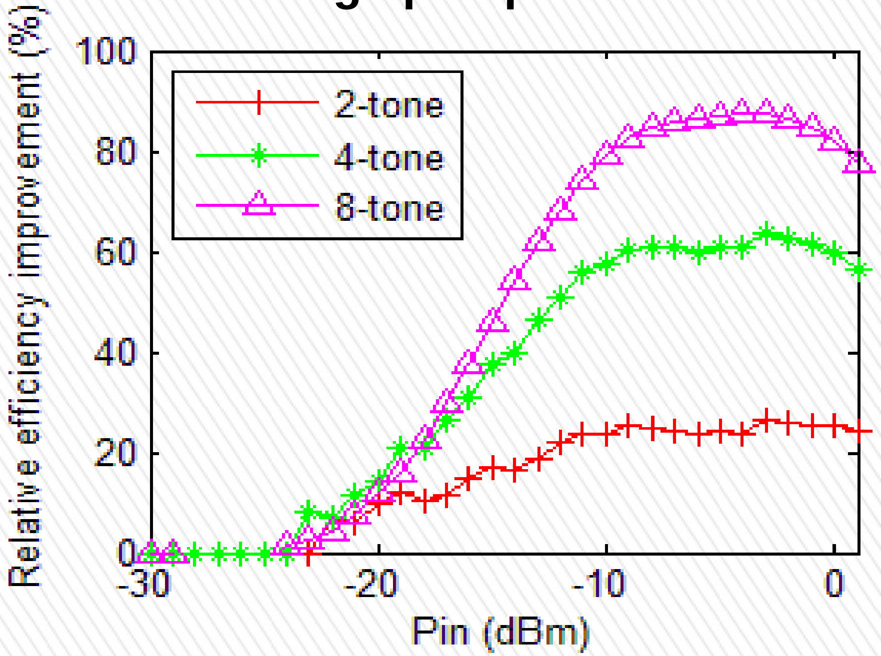
Two different circuits were built and tested:

Efficiency Gain: $$\Delta\eta = 100\frac{P_{DC_{MTone}} - P_{DC_{SC}}}{P_{DC_{SC}}}$$

A single diode detector at 2.4GHz

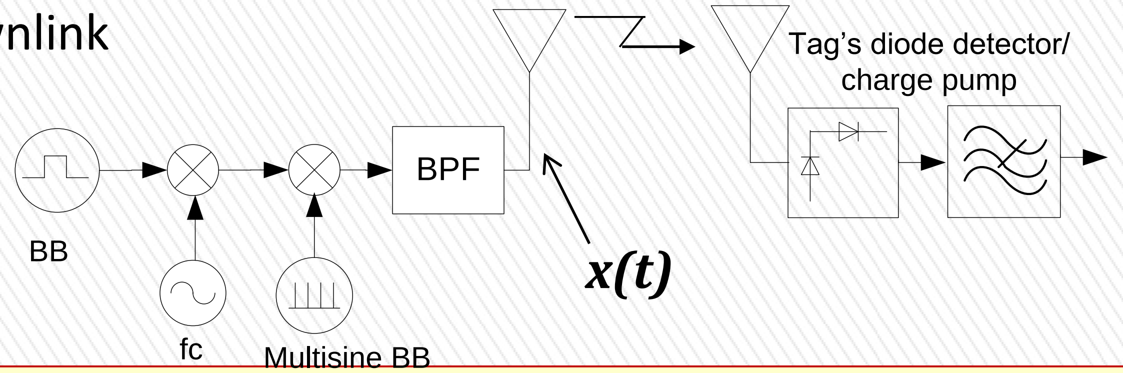


A charge pump at 866MHz



Use of Multi-sines in Circuit Design

RFID Downlink

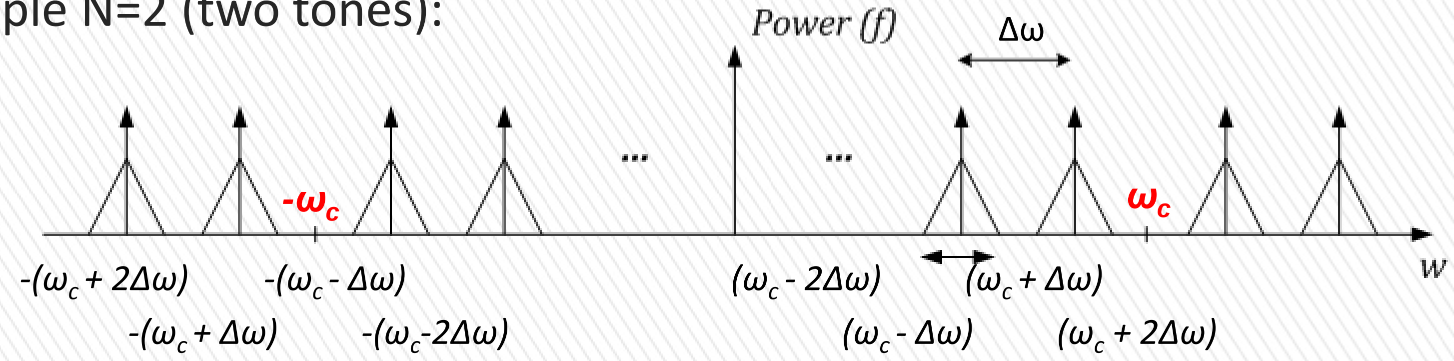


Transmitted signal:

reader's Baseband — Baseband Multisine — RF carrier

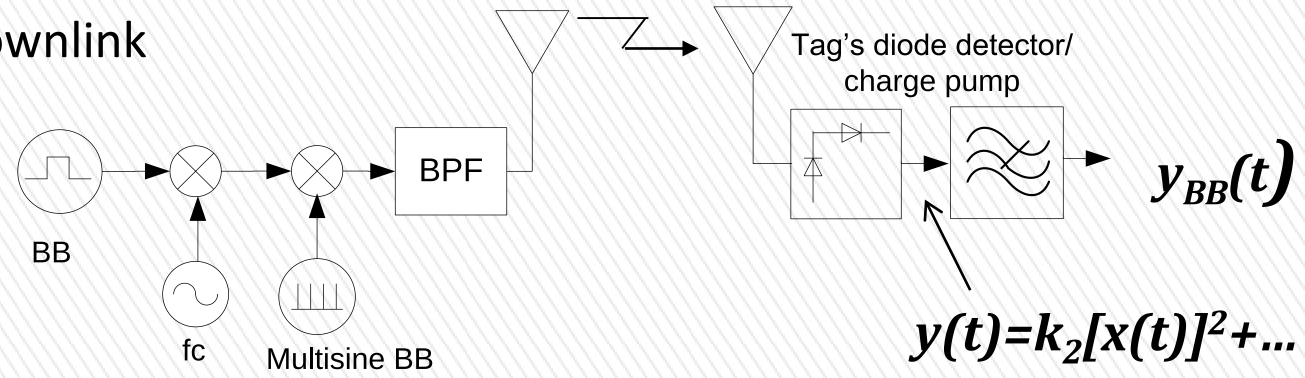
$$x(t) = m(t)\left\{\sum_{n=1}^{N} A_n \frac{e^{jn\Delta\omega t} + e^{-jn\Delta\omega t}}{2}\right\}\left\{A_C \frac{e^{j\omega_c t} + e^{-j\omega_c t}}{2}\right\}$$

for example N=2 (two tones):



Use of Multi-sines in Circuit Design

RFID Downlink



Signal at the Tag:

$$y(t) = k_2\left[m(t)\left\{\sum_{n=1}^{N} A_n \frac{e^{jn\Delta\omega t}+e^{-jn\Delta\omega t}}{2}\right\}\left\{A_C\frac{e^{j\omega_c t}+e^{-j\omega_c t}}{2}\right\}\right]^2$$

x(t) is squared by the Tag's diode detector

For N=2 (two tones), After low-pass filtering, the baseband is recovered by the Tag:

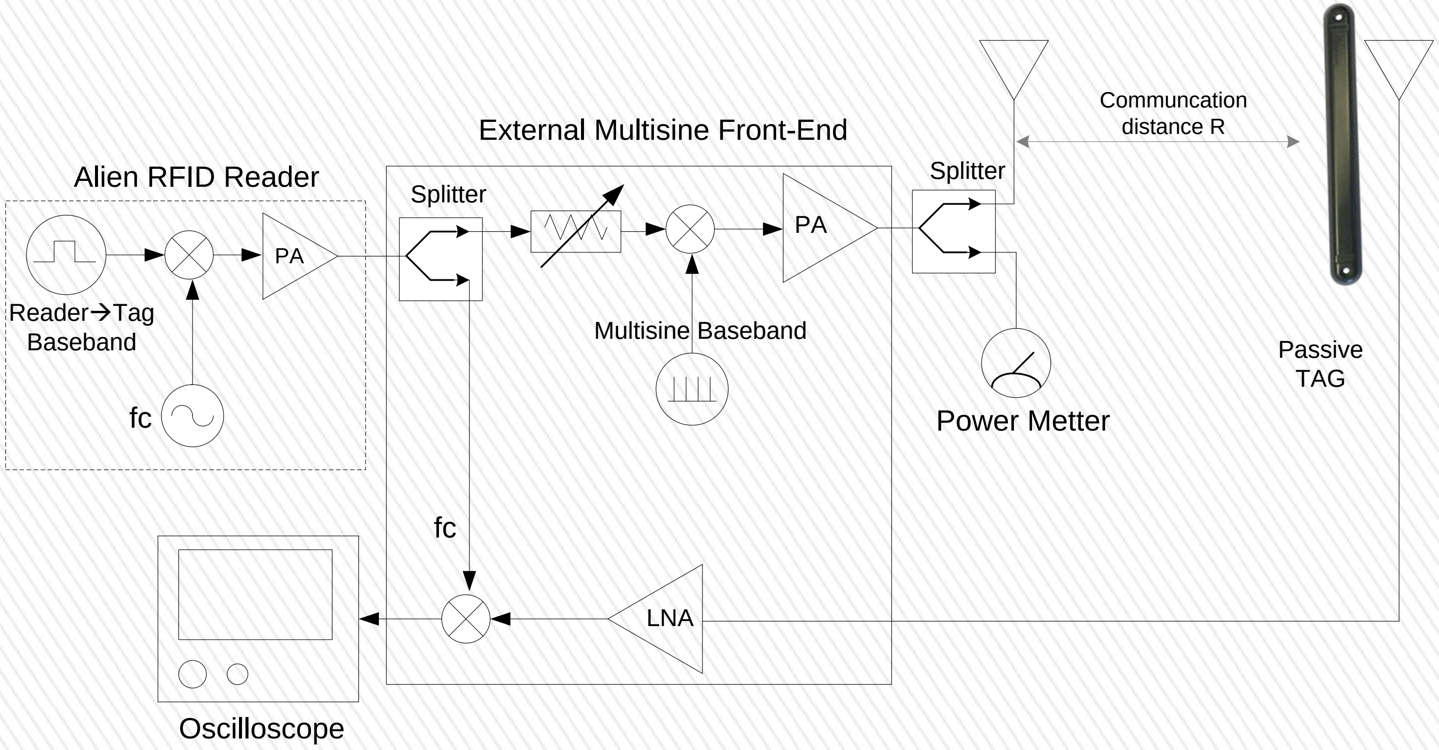
$$y_{BB}(t) = \frac{k_2}{4}[m(t)]^2(A_1^2A_c^2 + A_2^2A_c^2)$$

Use of Multi-sines in Circuit Design

SETUP 1:

- Downlink path fully implemented: RFID Reader + Multisine Front-End
- Tag Baseband Response is visualized in an Oscilloscope
- Communication range extension, r is estimated based on measured Tag Sensitivity Gain, G_P

$$r = R(\sqrt{G_P} - 1)$$



For fixed R, G_P = Minimum Power to activate Tag with CW – Minimum Power to activate Tag with Multisine

Use of Multi-sines in Circuit Design

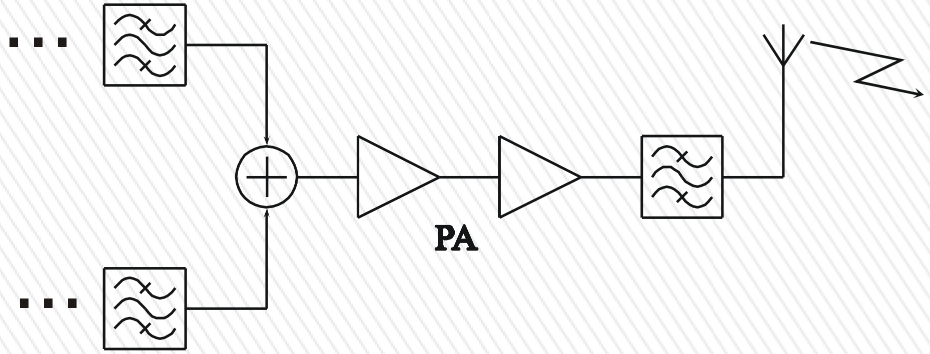
SETUP 1: Results

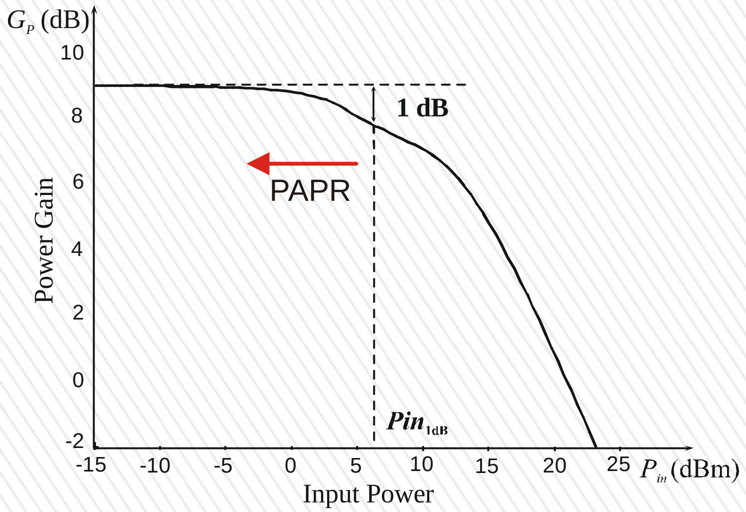
Reference fixed distance R=1.9m → P_{CW_min} =19.3 dBm

	Tone spacing, Δf (MHz)	Minimum Power P_{min} (dBm)	Tag Sensitivity Gain, G_P (dB)	Reading Range Gain r (m)	r (%)
CW		**19.3**	0.0	0.0	
2-tone	3.0	17.4	+1.9	+ 0.46	24.2
	2.0	17.5	+1.8	+ 0.44	23.2
	1.0	17.8	+1.5	+0.36	18.9
4-tones	3.0	16.5	+ 2.8	+ 0.72	37.9
	2.0	17.2	+2.1	+ 0.52	27.4
	1.0	17.7	+1.6	+0.38	20.0
8-tones	**2.0**	**16.2**	**+ 3.1**	**+ 0.81**	**42.6**
	1.0	16.4	+2.9	+0.75	39.4
	0.5	No response	-------	--------	--------

Use of Multi-sines in Circuit Design

- High PAPR signals saturate the PAs
- Saturation of PA implies:
  - Reduction of Peaks
  - Reduction of Efficiency

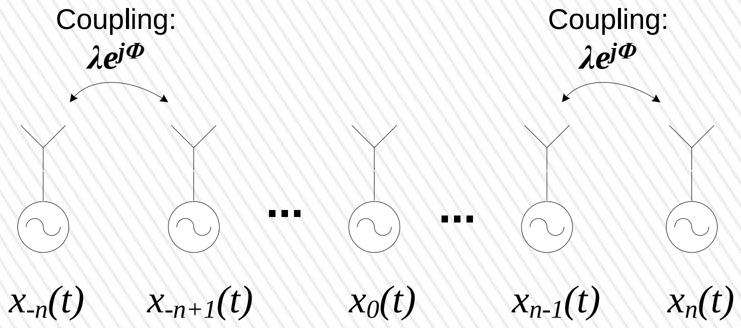




Use of Multi-sines in Circuit Design

Spatial Power Combining for WPT

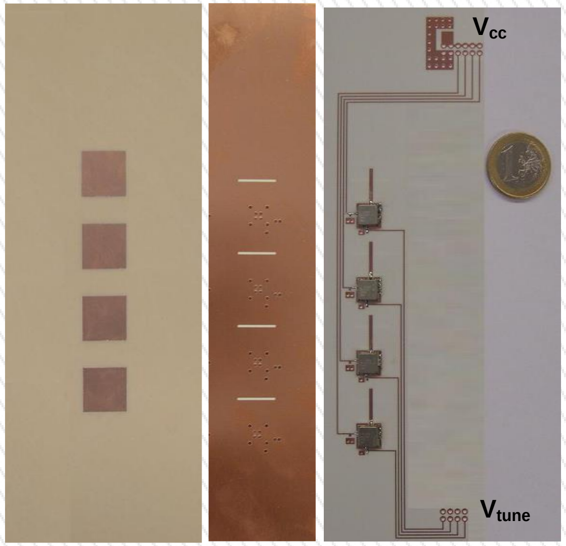
- High PAPR signals saturate the PAs
- Spatial power combining – each tone amplified independently and then combined in free space
- Mode-locked coupled oscillators – establish phase reference and control phase shift among elements



Use of Multi-sines in Circuit Design

Spatial Power Combining for WPT

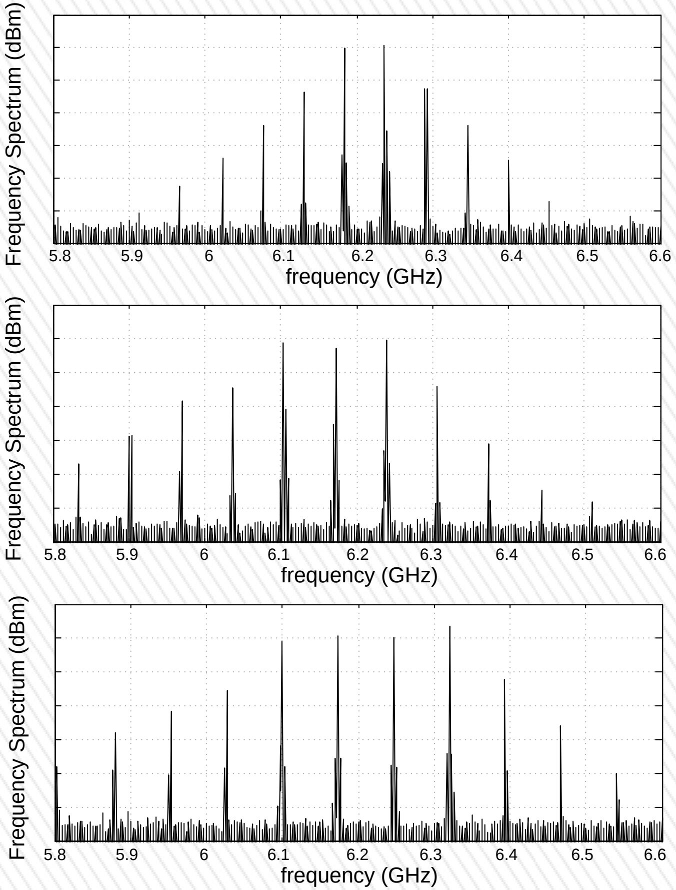
- 4x1 active antenna oscillator array at 6 GHz
- Patch antenna aperture coupled to a VCO



Use of Multi-sines in Circuit Design

Spatial Power Combining for WPT

- Step1: 2 VCOs with 50 MHz spacing. Mixing products are created
- Step2: 3 VCOs. The third one with a free running frequency corresponding to one of the mixing products
- Step3: 4 VCOs. The fourth one with a free running frequency corresponding to one of the mixing products

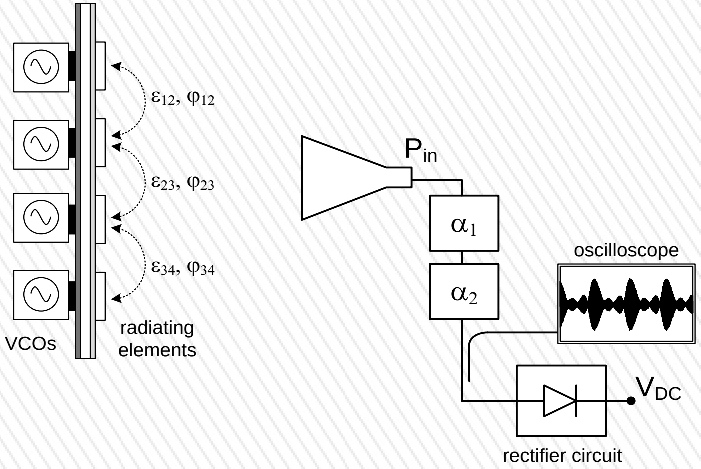


Ana Collado and Apostolos Georgiadis

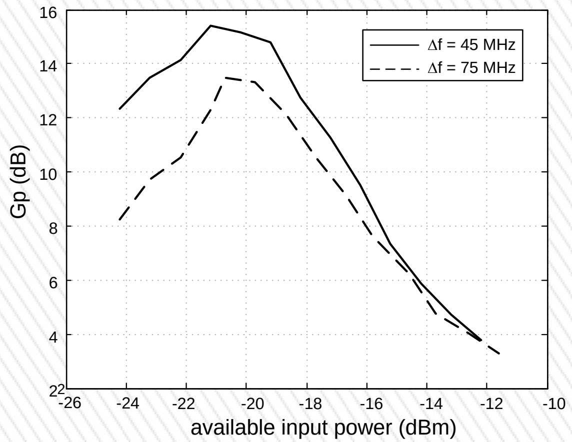
Use of Multi-sines in Circuit Design

Spatial Power Combining for WPT

- Power gain compares the obtained DC voltage by a rectifier when using the high PAPR signal in comparison with a one-tone signal
- Improved performance when using the high PAPR mode-locked signal



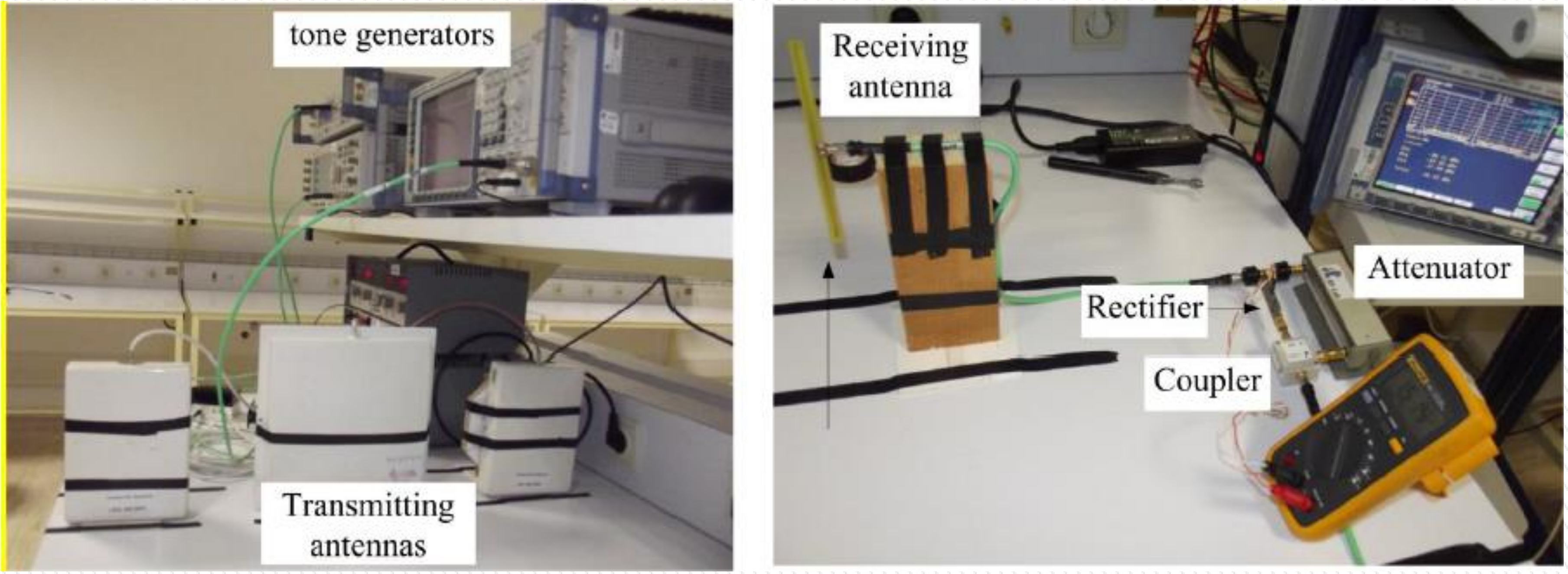
$$G_{P1}(dB) = 10 \cdot log10\left(\frac{P_{DC\,(N)}}{P_{DC\,(1)}}\right) = 10 \cdot log10\left(\frac{V^2_{DC\,(N)}}{V^2_{DC\,(1)}}\right)$$



Ana Collado and Apostolos Georgiadis

Use of Multi-sines in Circuit Design

Spatial Power Combining for WPT



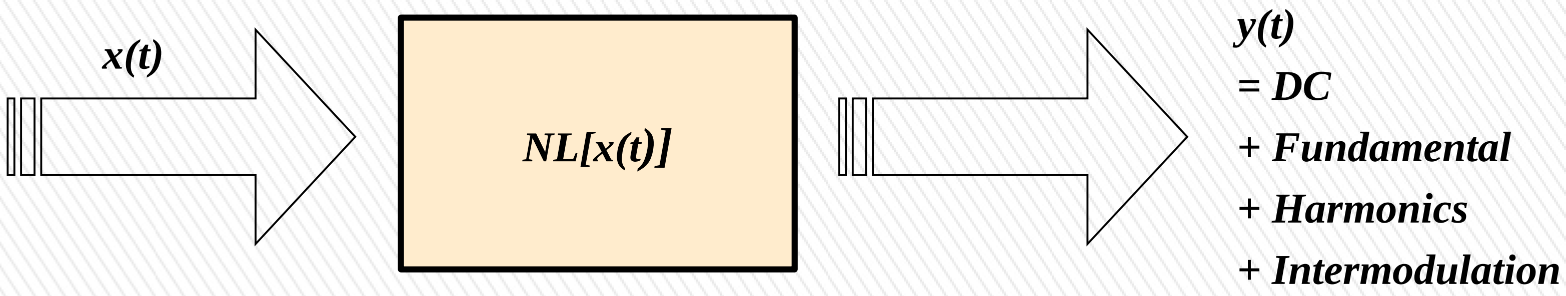
Characterizing RF-DC Converters …

The need for modeling

- We are always interested in the RF-DC characteristic

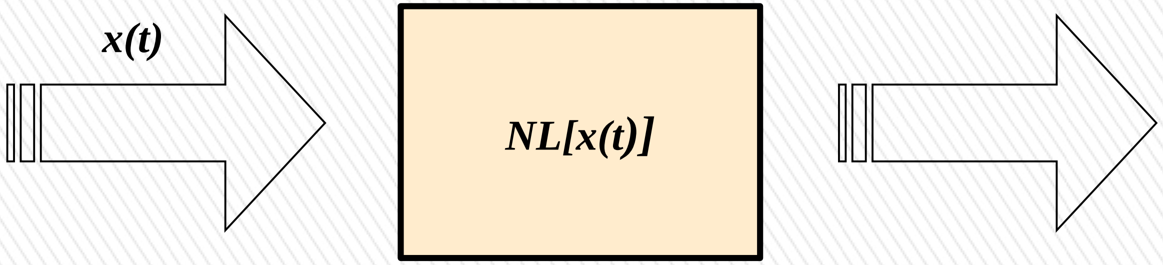
- So, it would be nice if such characteristic could be described by a black box approach

- Behaviorally speaking: The active device is a non-linearity:



The need for modeling

- The active device is a non-linearity:



y(t) = **DC**

+ Fundamental

+ Harmonics

+ Intermodulation

- Here, the Nonlinear Device will be described by an Even-Order Memoryless Taylor Series:

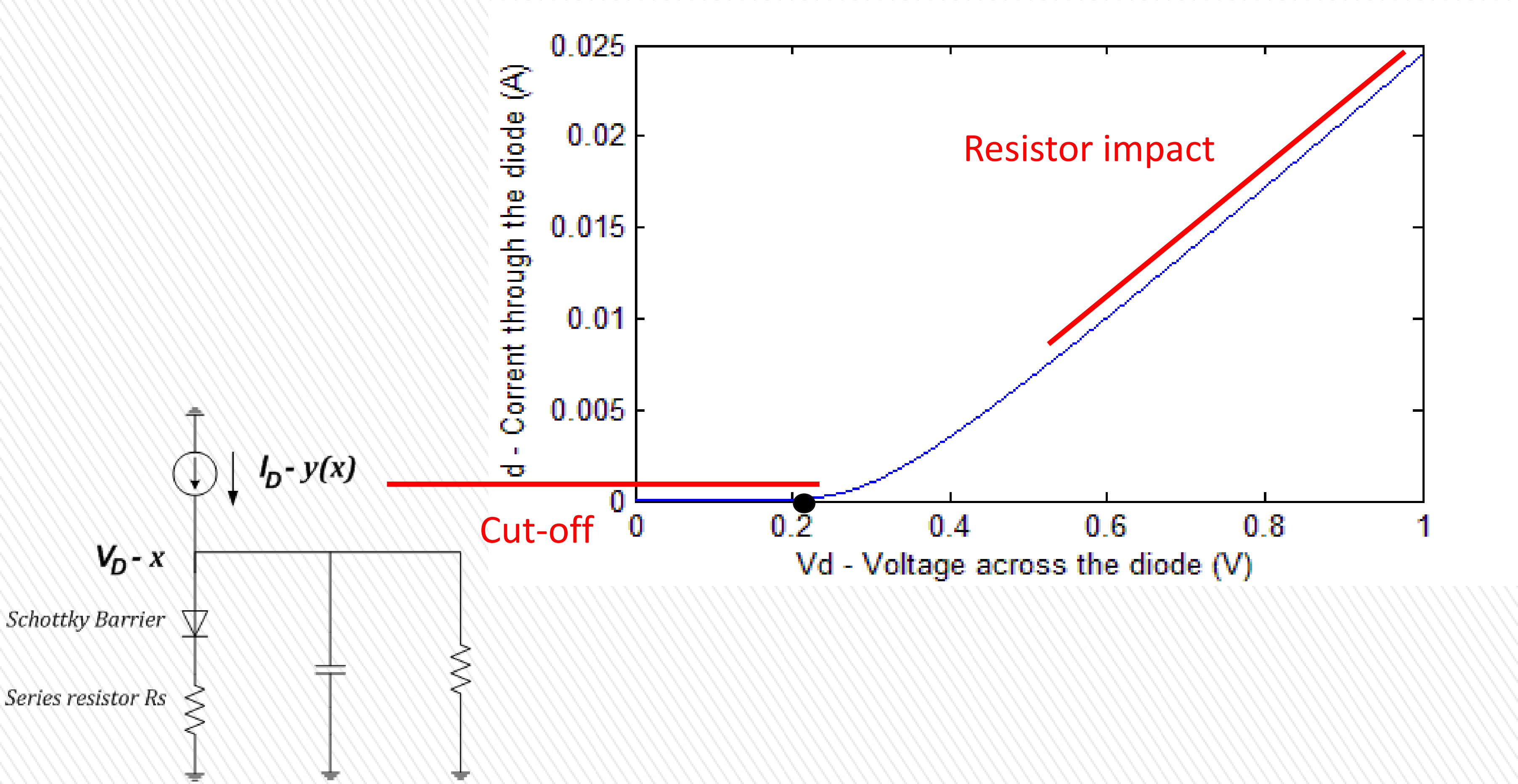
$$y(t) = \sum_{n=1}^{N} k_{2n} x(t)^{2n}$$

… it can be proved that only even-order terms contribute to DC

Improve the Circuits Nonlinear Modeling

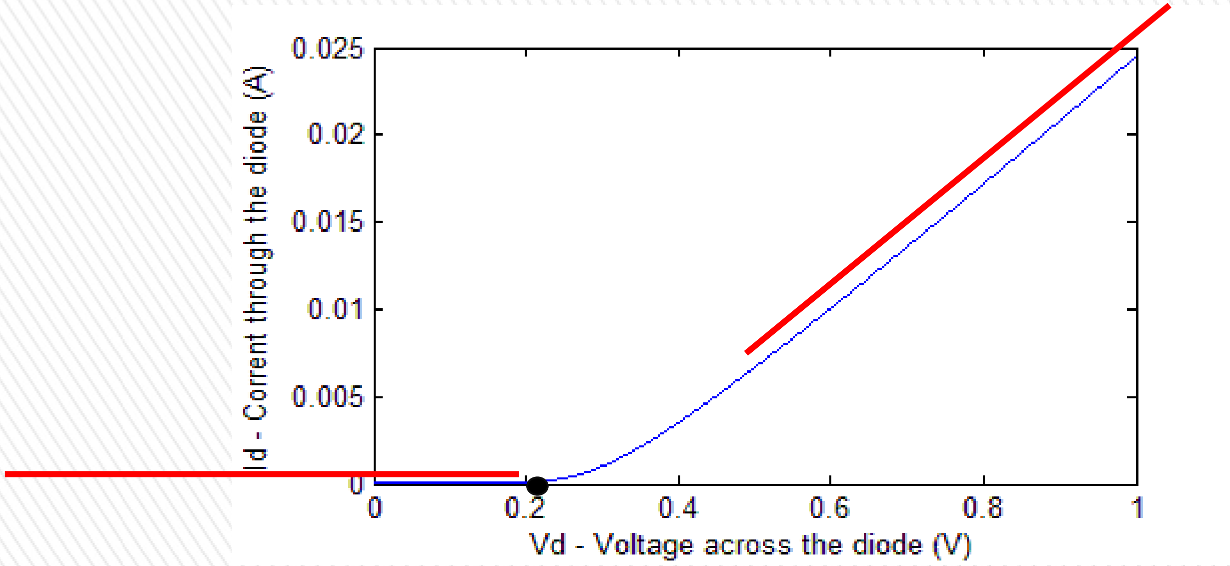
RD-DC converters rely on non-linear devices.

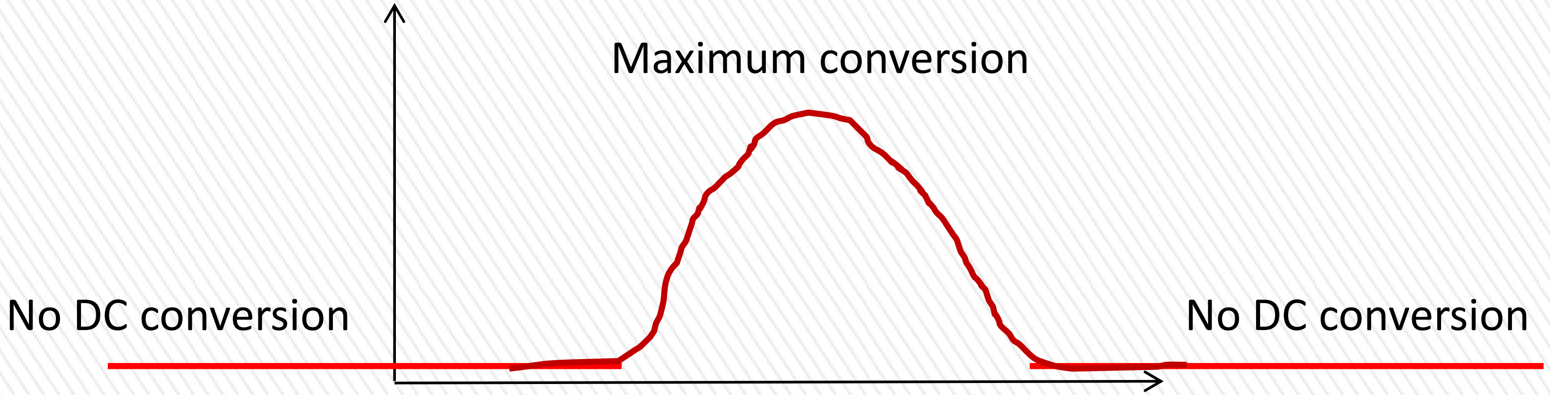
The simplest configuration uses a single Schottky diode.



nbcarvalho@ua.pt

Improve the Circuits Nonlinear Modeling





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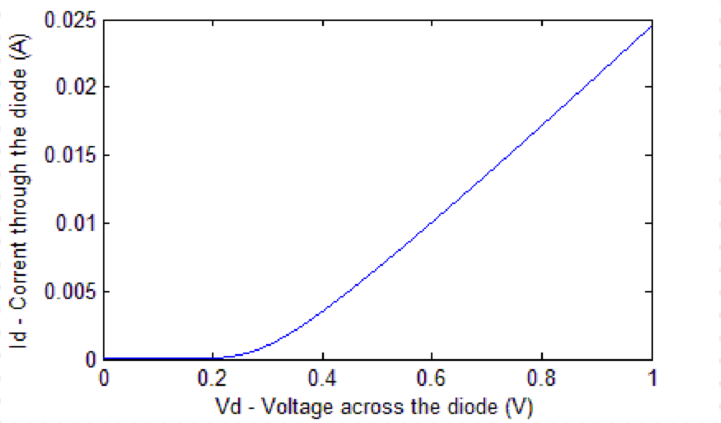
The need for modeling

- Taylor series can be expanded around a quiescent point,

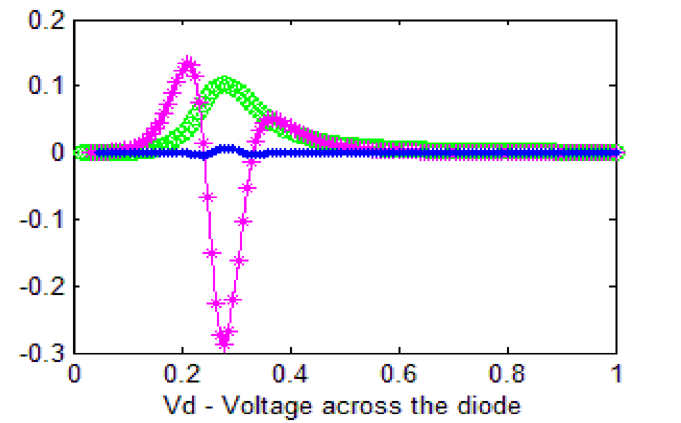
  Hence, the model coefficients can be obtained:

$$k_n = \frac{1}{n!}\frac{\partial^n y(x)}{\partial x^n}\bigg|_{x=X_q}$$

y(x) is the diode DC I-V characteristic curve

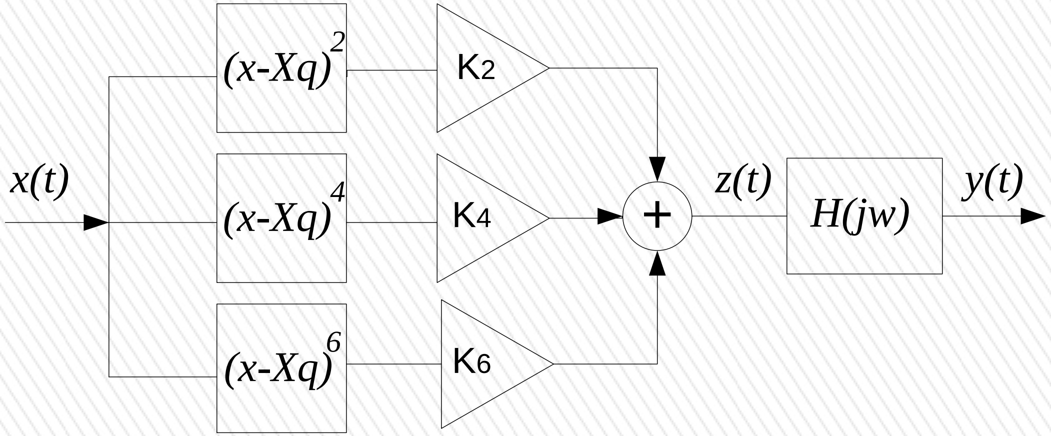


First three even-order coefficients (k_2,k_4 and k_6)



The need for modeling

- General Model Structure for the RF-DC converter



$$z(t) = \sum_{n=1}^{3} k_{2n} x(t)^{2n}$$

$$k_n = \frac{1}{n!} \frac{\partial^n y(x)}{\partial x^n}\bigg|_{x=X_q}$$

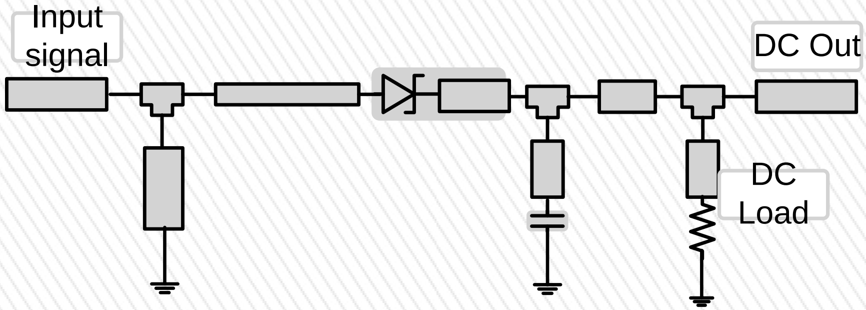
- Since we are only interested in the DC at *y(t)*, an ideal low-pass filter *H(jw)* is considered at the output

Characterizing RF to DC Converters

These systems are highly nonlinear so better and improved systems for nonlinear characterization combining RF and DC are fundamental.

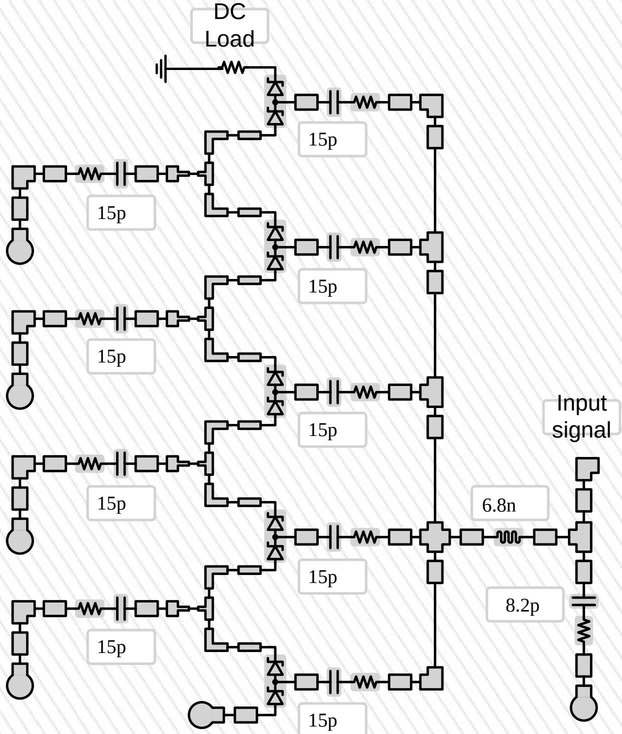
A single diode detector at 2.4GHz

(typically used in energy harvesting)



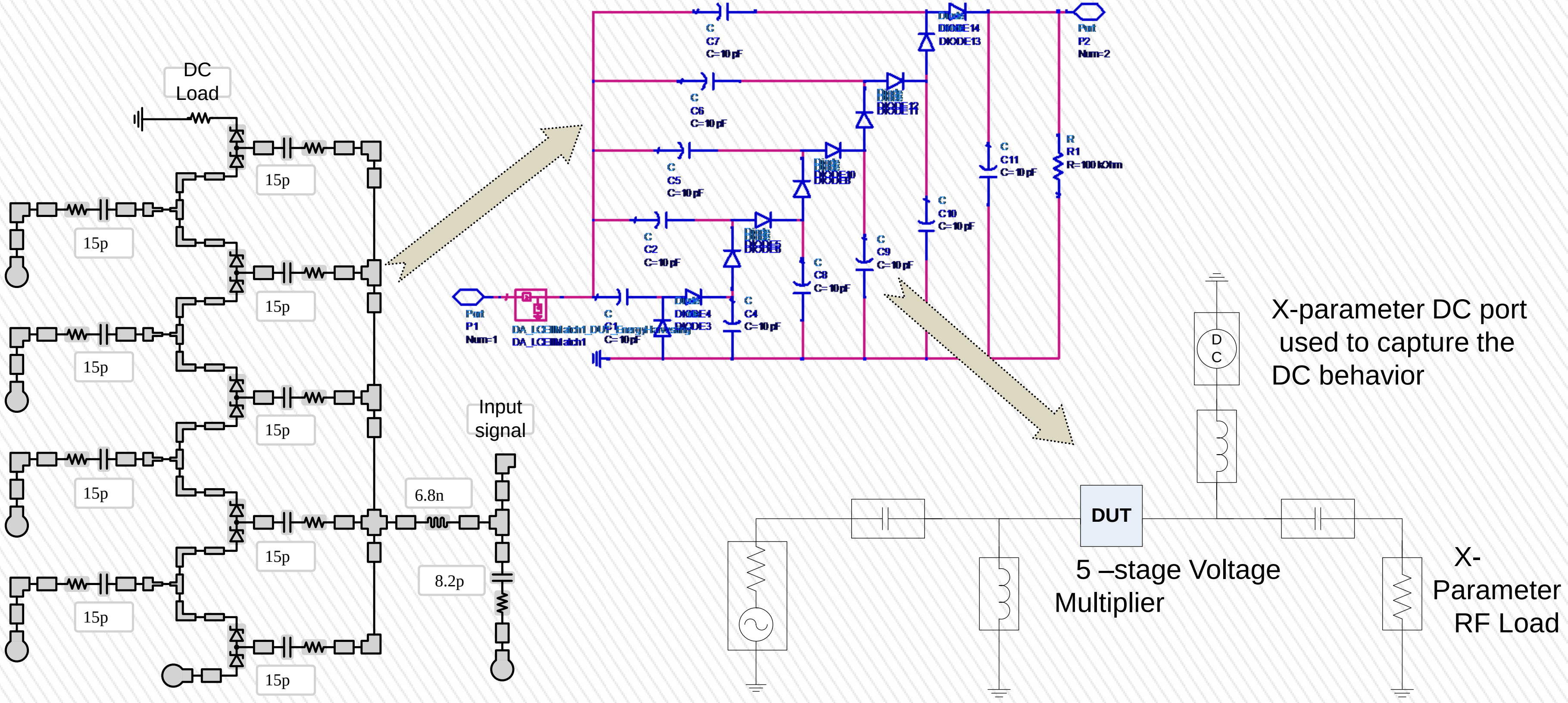
A charge pump at 866MHz

(typically used in RFID Tags)



Characterizing RF to DC Converters

The full system should be included into a simple simulation model

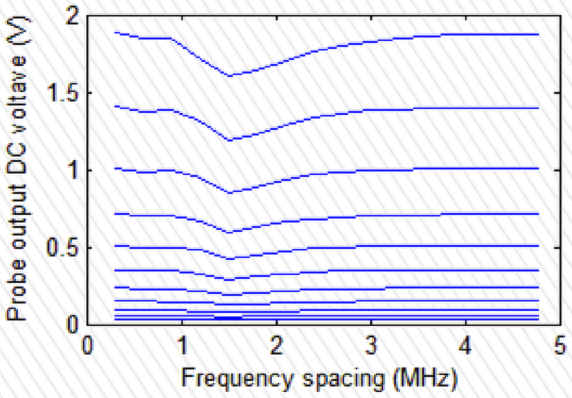


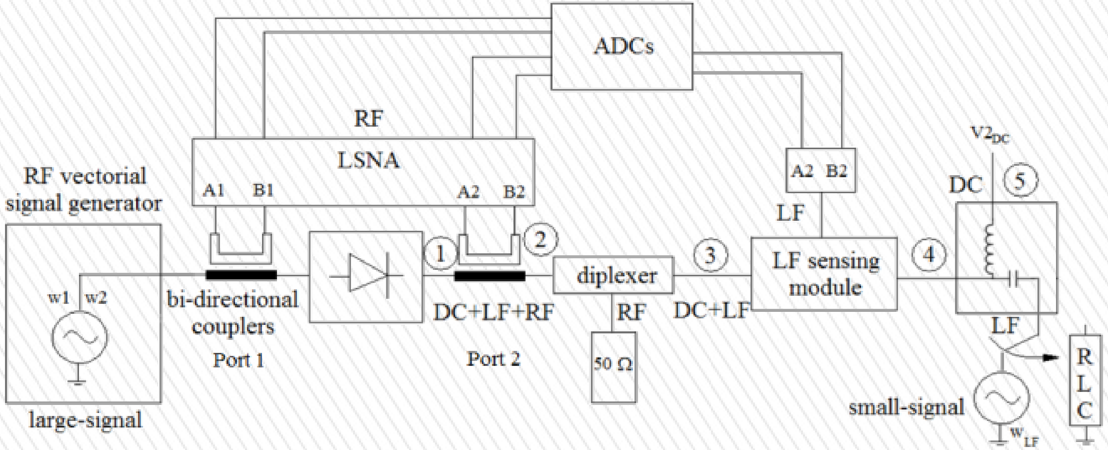
X-Parameter Power Source
-40dBm:-10dBm
400MHz – 1800MHz

Characterizing RF to DC Converters

In this case the input signal is a radio-frequency signal, while the output is a DC voltage

DC (V) measured with an LSNA





The depth in the curves coincides with the resonance frequency of the detector output impedance

Alejandro Testera and Monica Barciela, University of Vigo, Spain

Characterizing RF to DC Converters

LSNA Setup used to extract a X-model from a real world detector

Main Blocks:

4 – Input BiasTee

5 – Output BiasTee

6 – DC bias Module

8a – Large Signal Generator which imposes the LSOP at Port 1

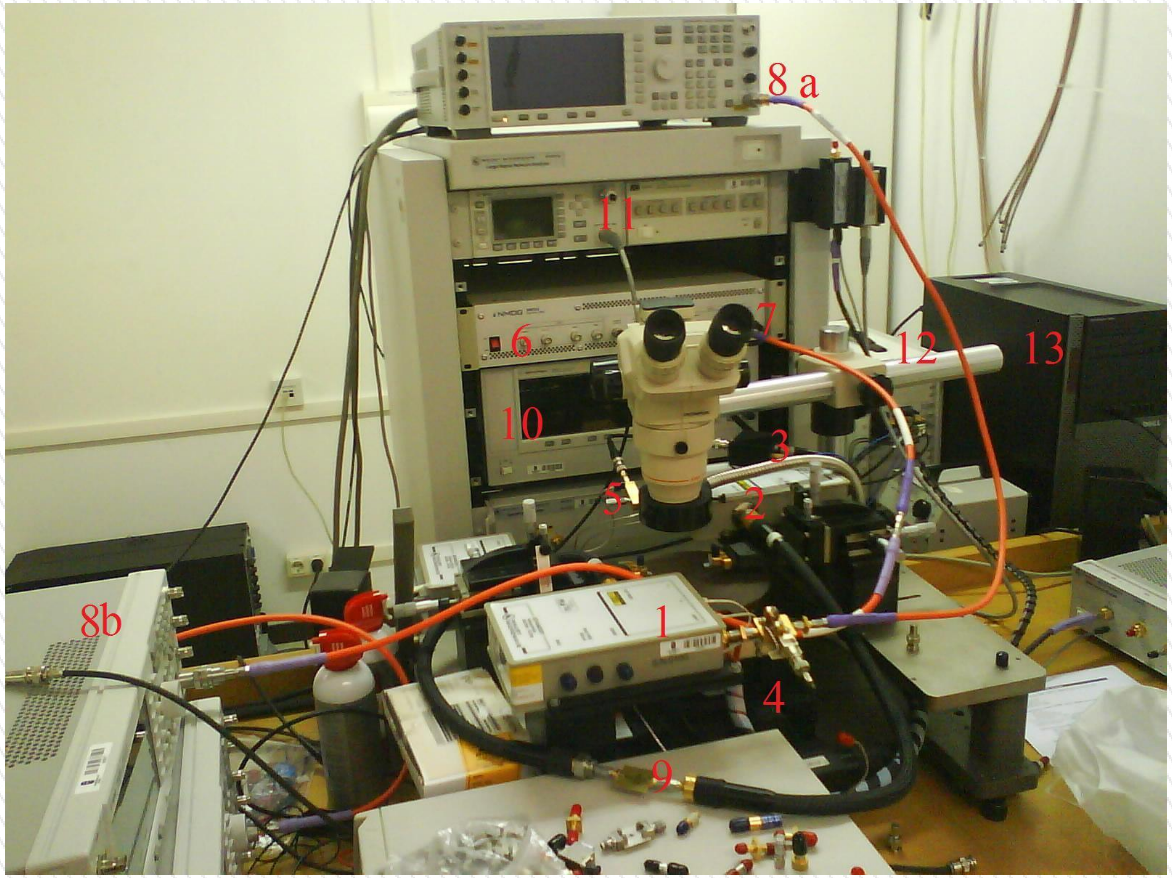
8b – Small Signal Generator

9 – DUT: detector

11 – Power Sensors and Attenuators

12 – ADC's

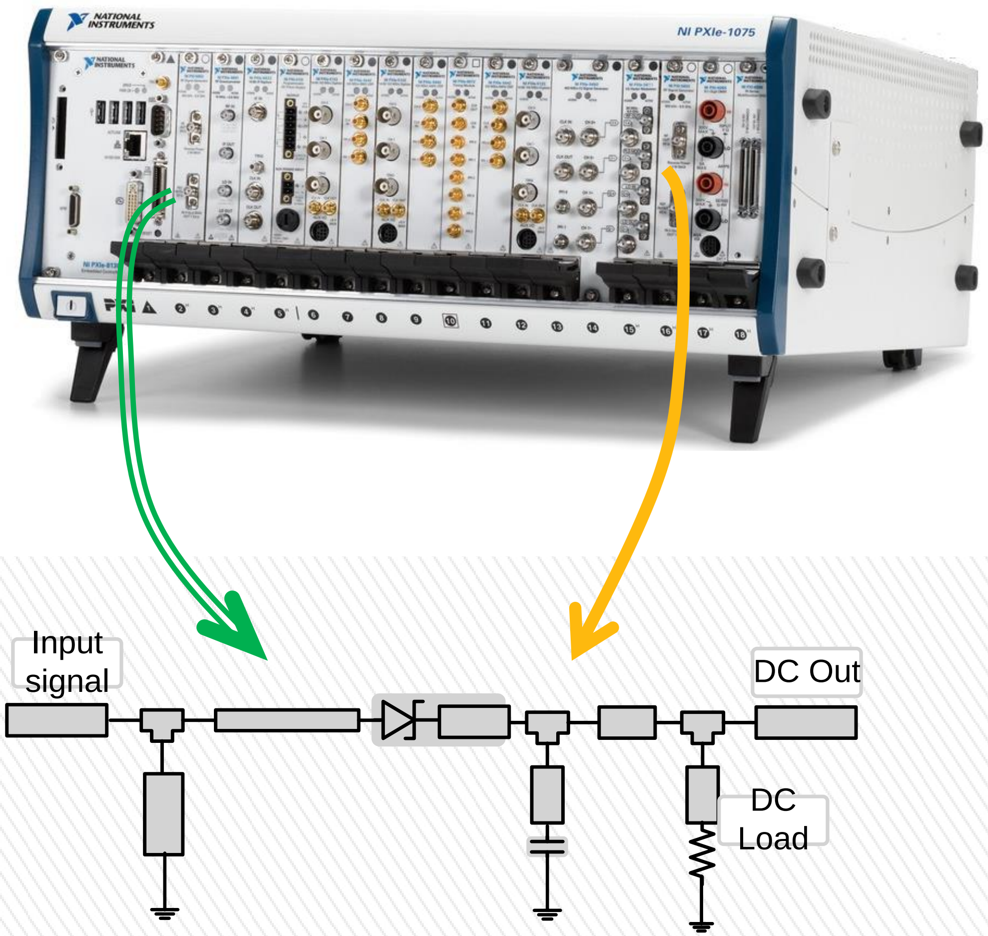
13 – System Computer



Alejandro Testera and Monica Barciela, University of Vigo, Spain

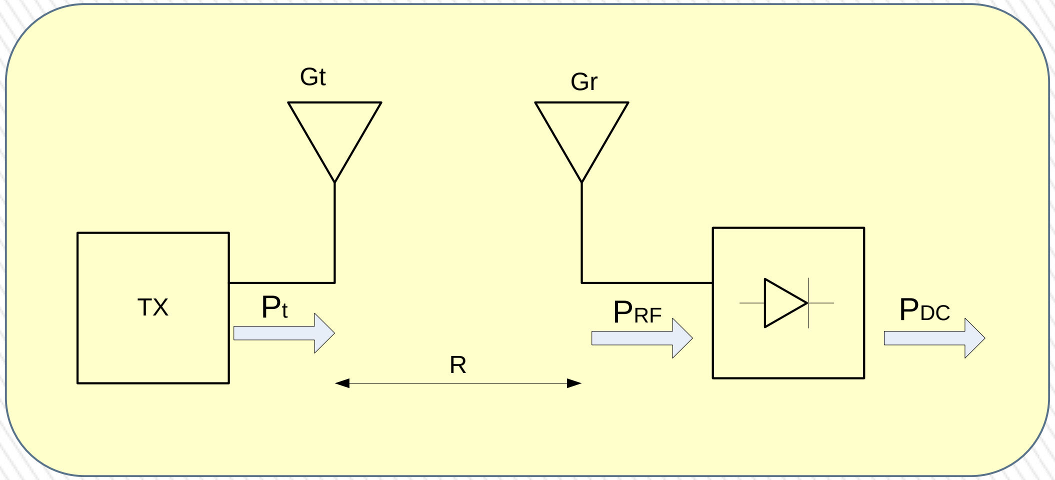
Characterizing RF to DC Converters

A viable instrument can be built using RF and DC approaches …



How can this be used in Space …

Power Generation



Efficient Generation of Power in Space Environments.

Communication Satellites

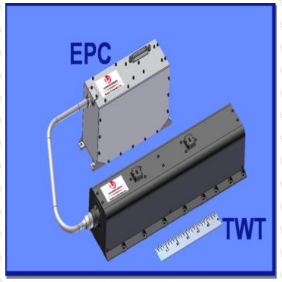
Amplifiers continue to be TWTA’s

- Heavy
- Huge

Communication Satellites

Travelling Wave Tube Amplifiers – TWTA –…

Technology Evolution

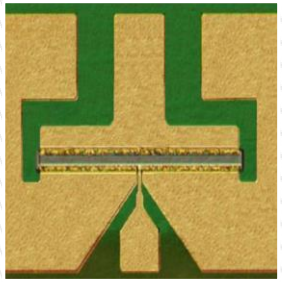


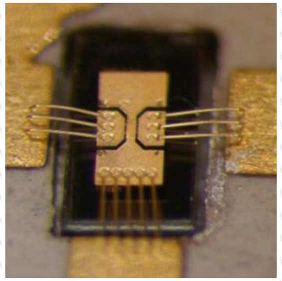
TWTA

Heavy, Expensive, Huge …

GaAs

Low Power, interesting low noise





GaN

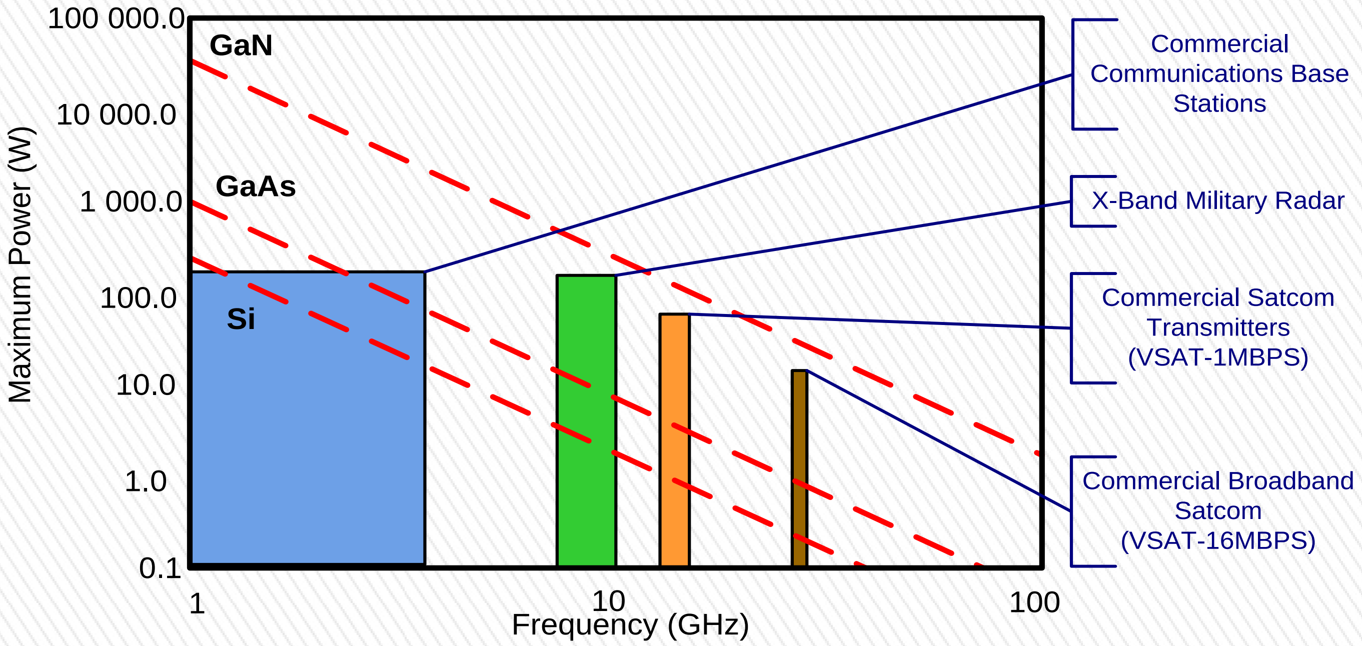
High Power and potential good low noise

Technology Evolution

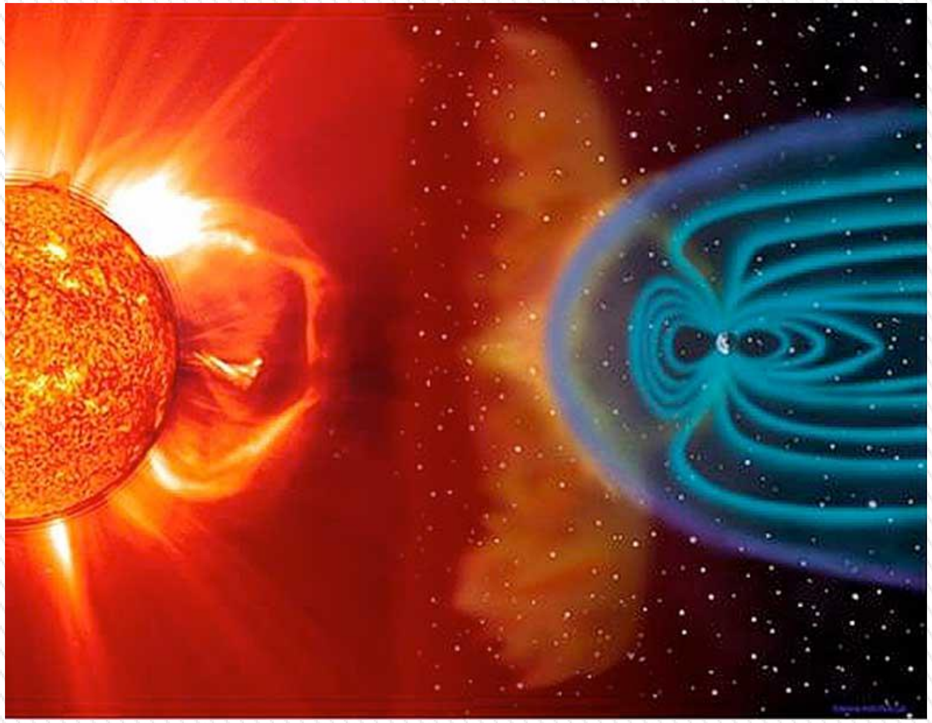
Why GaN in Space ?

Power and Frequency limits to :

Si, GaAs e GaN



Technology Evolution

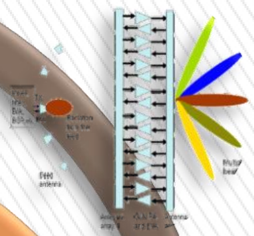


GaN should be tested in Space Environments and radiation hardness.

IT GaN Projects

IT-Aveiro

Radio Systems Group



GANSAT: GAN MMIC

Develop GAN MMIC for Space Communications, with Space Power Combining.

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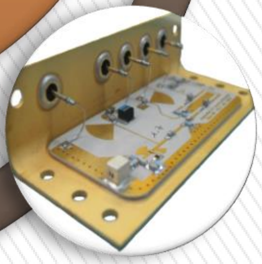

GaNSpace: GaN Oscillator for Space Evaluation

Propose and evaluate GaN technology for space applications. A GaN transistor prototype will be implemented as an oscillator to be tested in space for reliability

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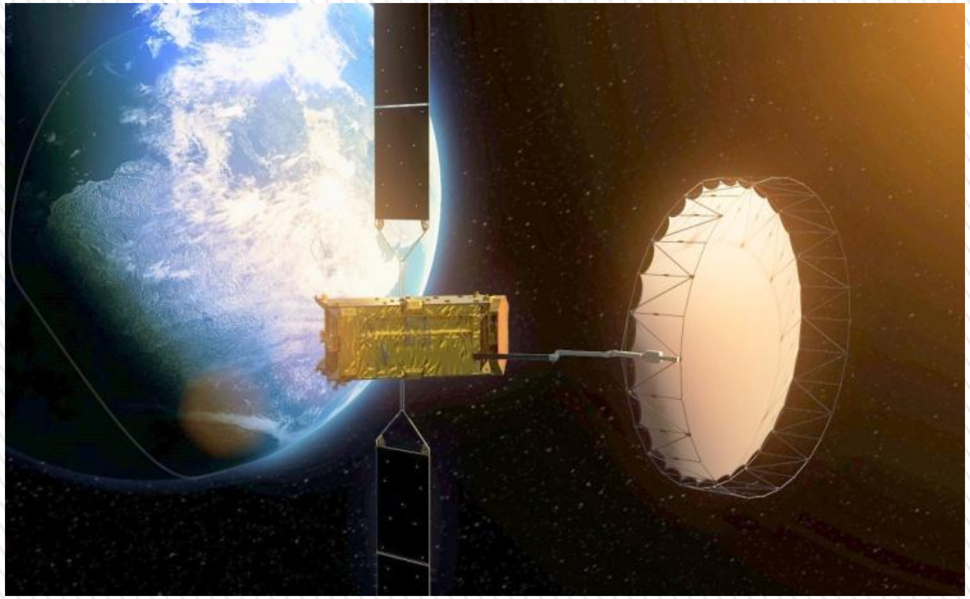
radio systems

radiosystems.av.it.pt/

Alphasat Project

» AlphaSat participants



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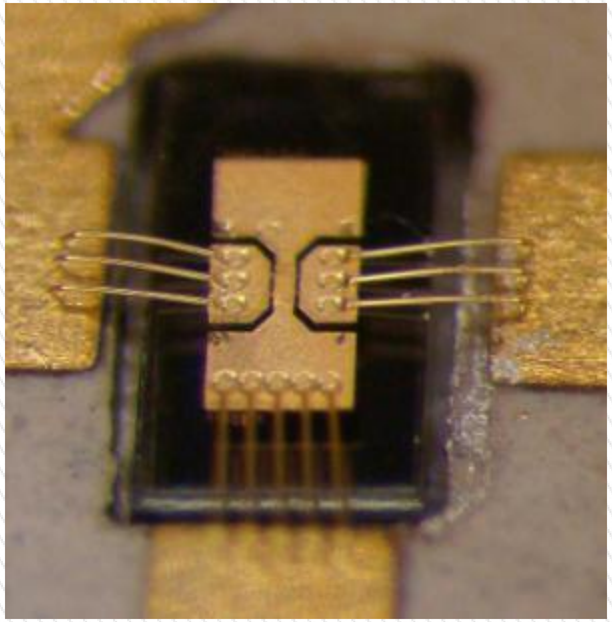
Introduction and motivation

The main objective of the project is to test GaN Technology in space, mainly European versions.

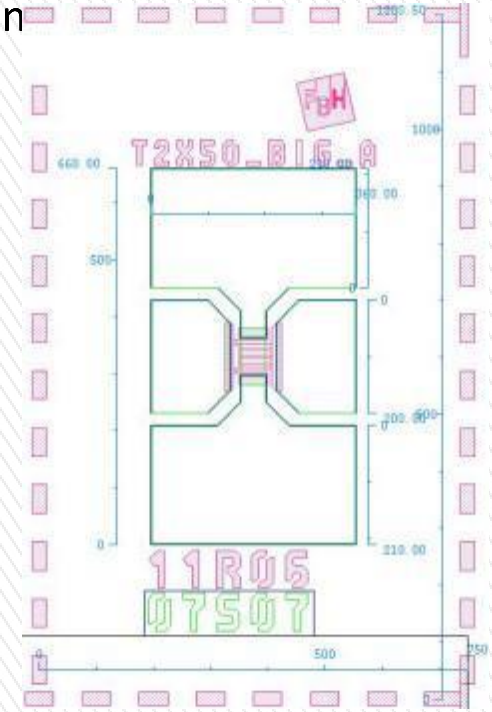


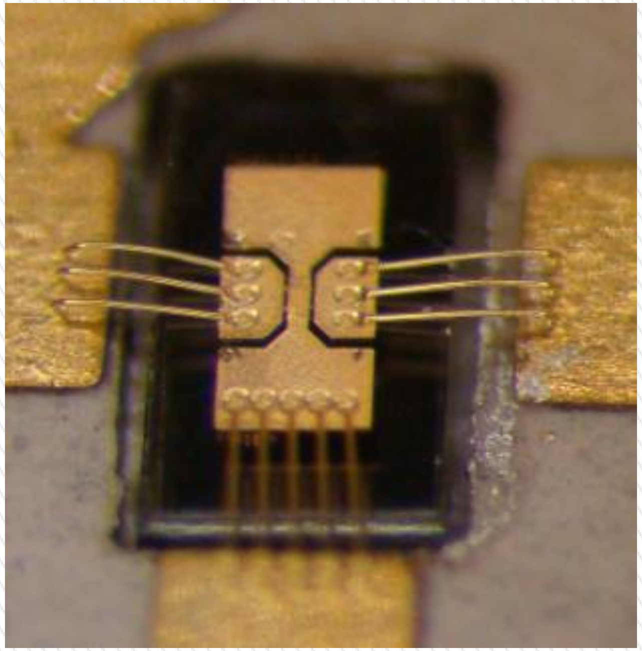
GaN Technology

- Transistor technology suplied by FBH

  (Fredinand-Braun-Institut)

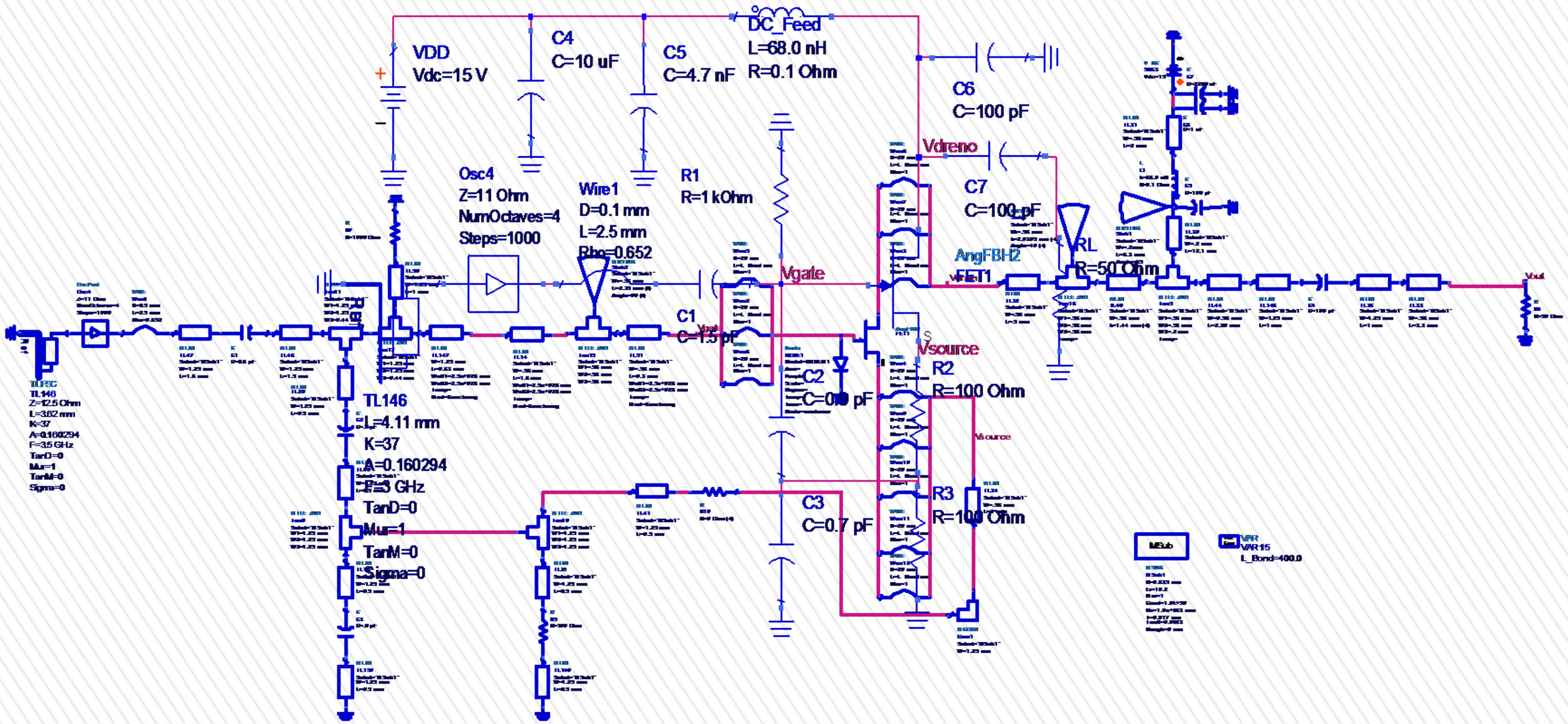
- Cosmic radiation immunity
- High frequency operation
- High power handling





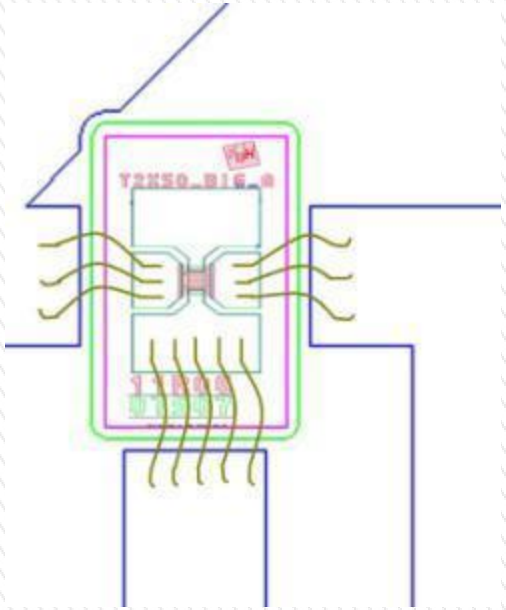
Oscillator Circuit

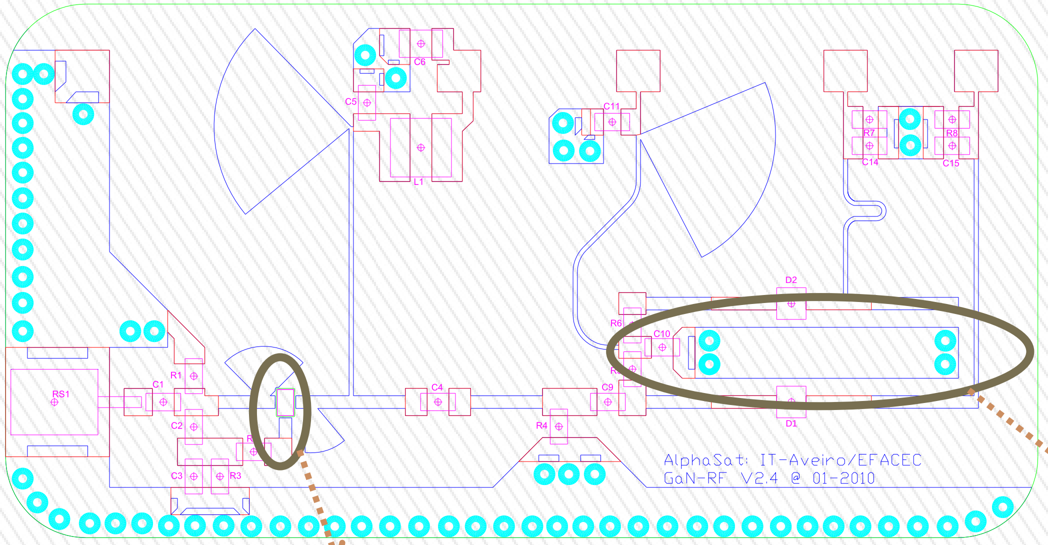
- Oscillator based on traditional Colpitz configuration
- Frequency of oscillations imposed by payload restrictions (near 2GHz)
- Ceramic resonator for high Q



Oscillator Circuit

- Prototype should consider high frequency oscillations due to impressive transistor quality
- Oscillations near 12-15GHz.





Stubs for high frequency spurious reduction

Measurement circuit
Power measurement

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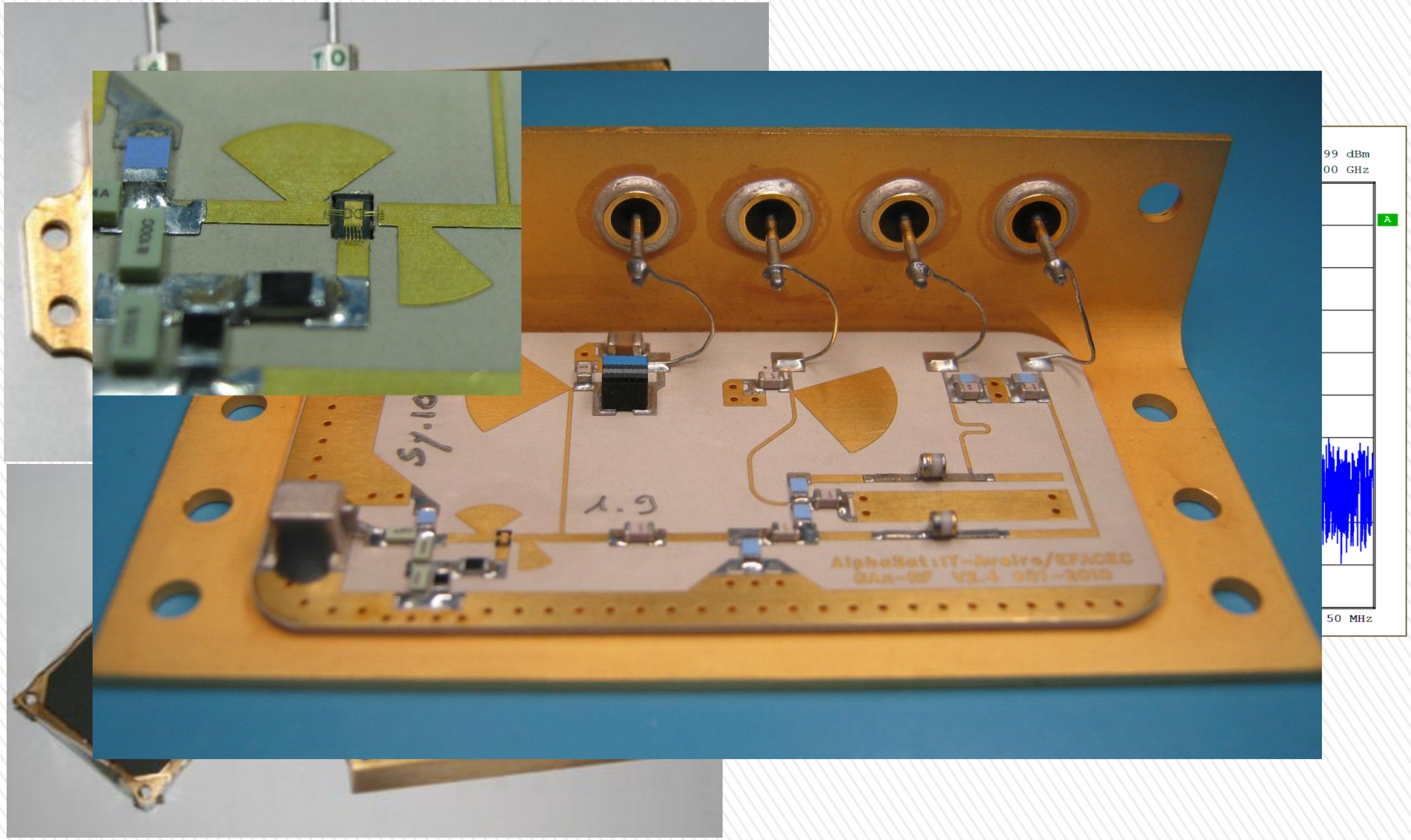
Oscillator Prototype

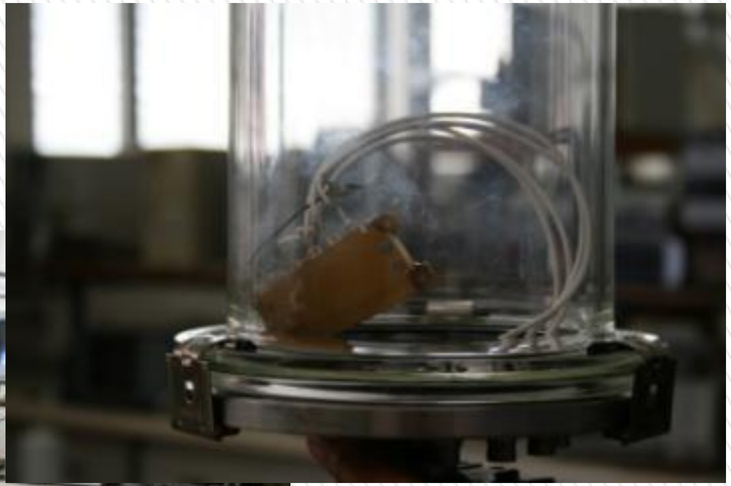


Oscillator Prototype

Vacuum tests

To avoid any particles or gases released

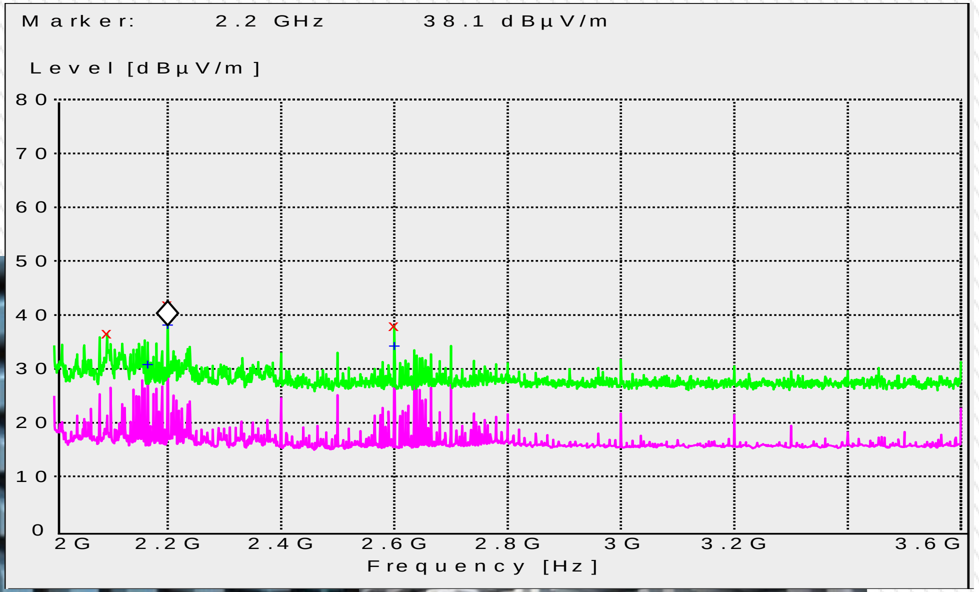
not expected

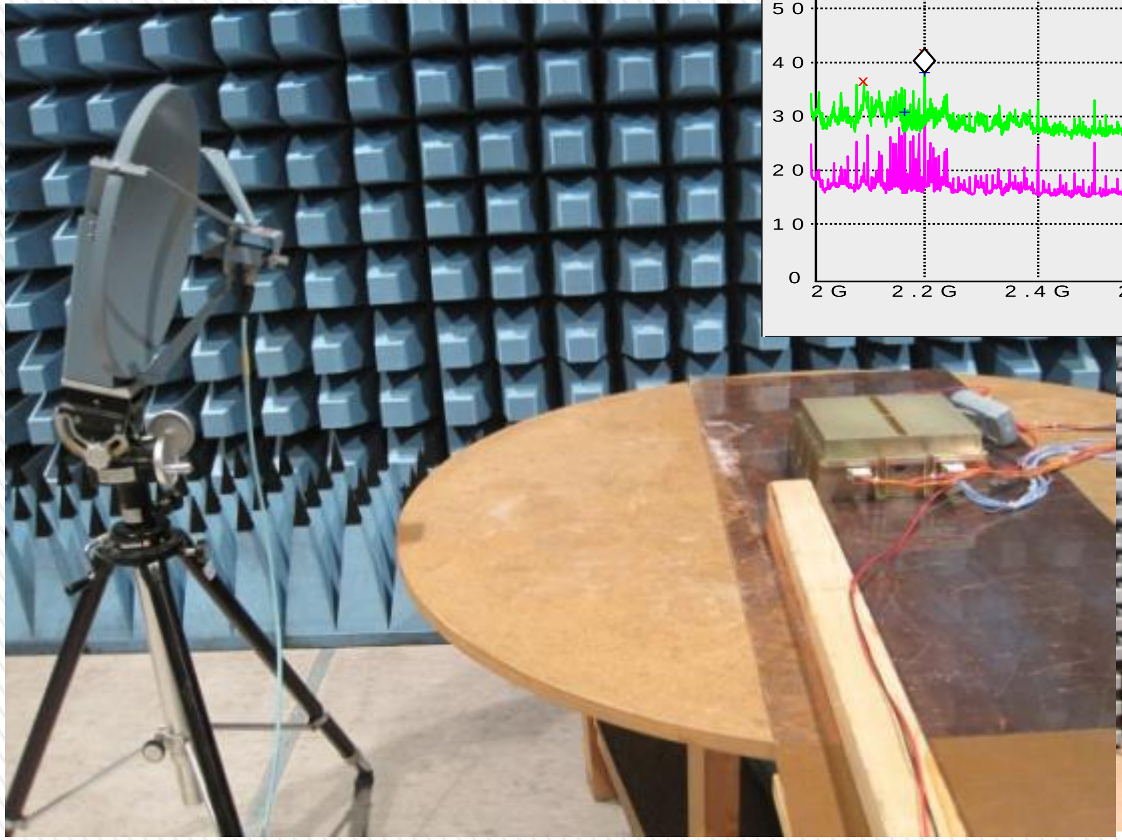


Oscillator Prototype

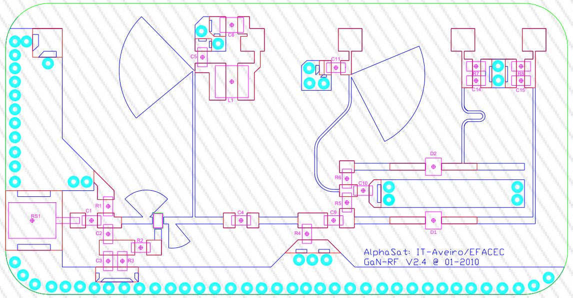
EMC tests

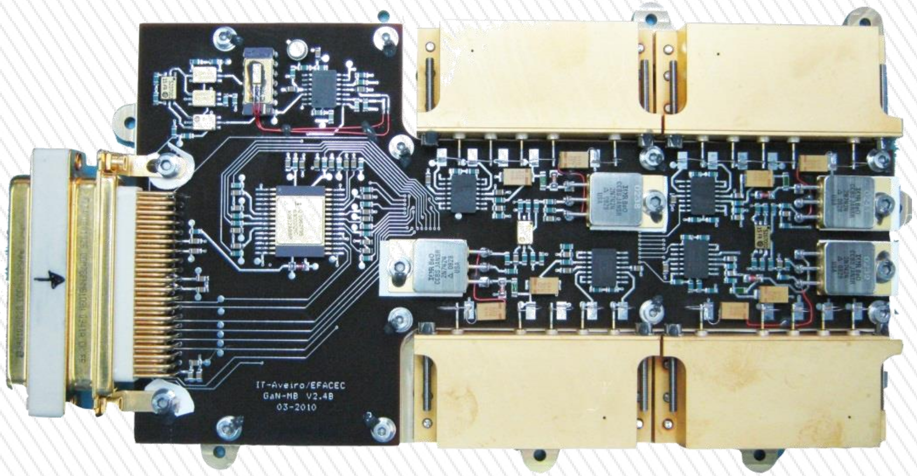
- US Military, agreement concern

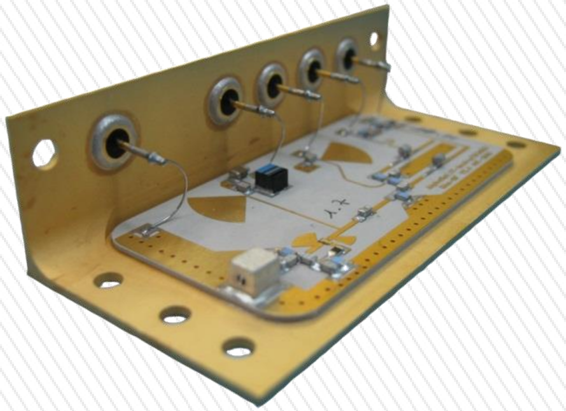




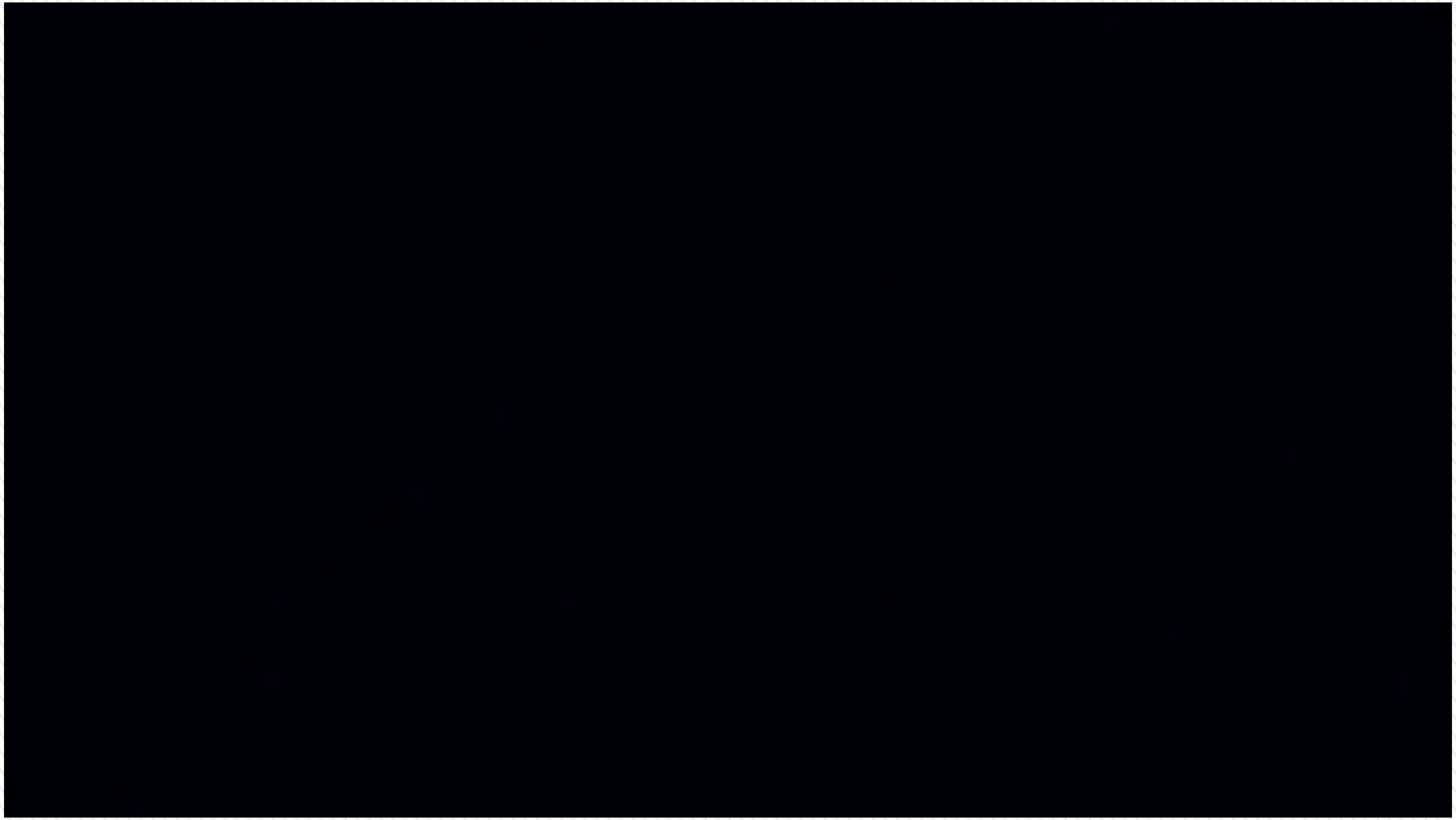
Final prototype





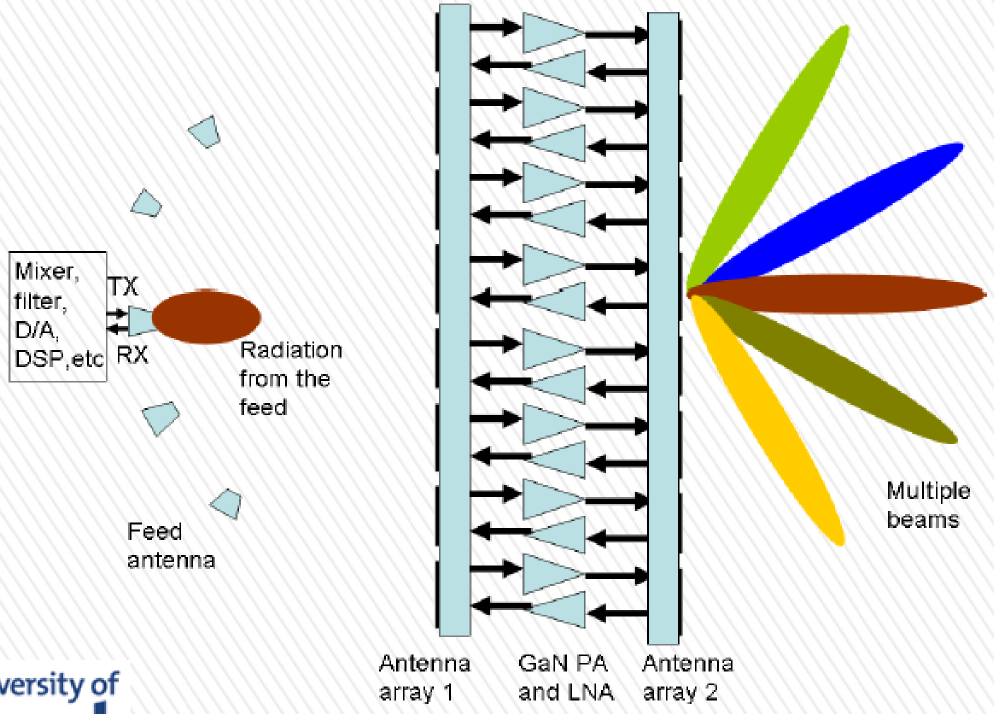


Final prototype



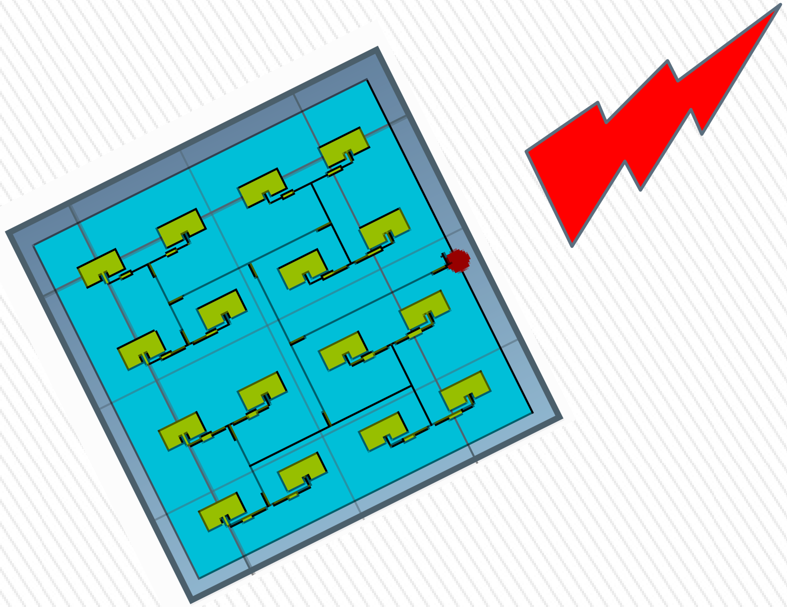
GaNSAT

GaNSAT: High Power MMIC using Space Power Combination



PARTNERS:

Drone WPT



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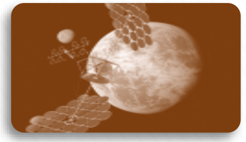
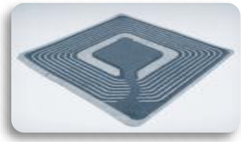
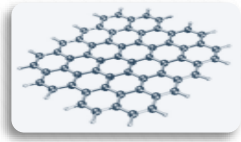

WG1: Far-field WPT systems

WG2: Near-field WPT Systems

WG3: Novel Materials and Technologies

WG4: Applications

WG5: Regulation and Society impact

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