Wireless Power Transmission
Creation of Focus Energy

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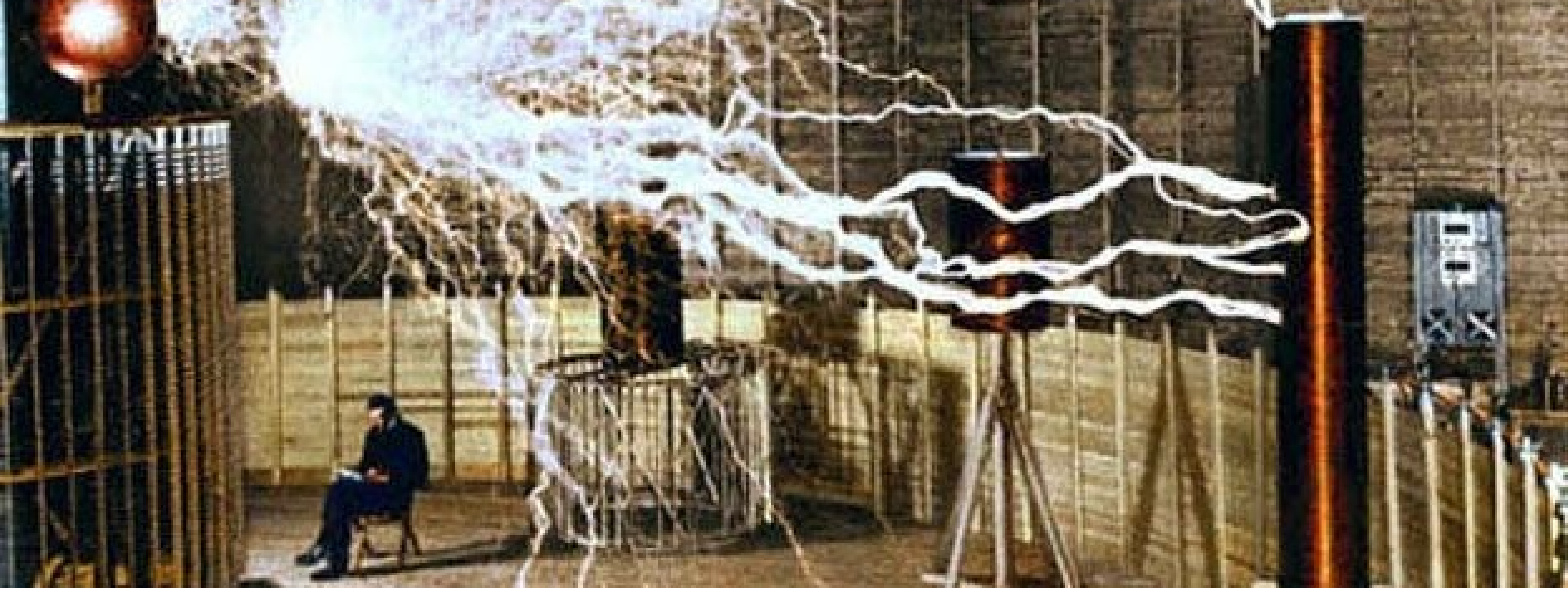
Outline

1. Historical Introduction and Current Trends
2. Types of WPT
   i. Inductive Coupling
   ii. Radiative Near-Field
   iii. Radiative Far-Field
3. Energy efficient Far-Field WPT Developments
   i. A Selective, Tracking and Power Adaptive WPT system



I. Historical Introduction and Current Trends

History

- Electricity science goes back to 600BC, when Greeks saw that a rubbed piece of amber will attract a bit of straw

- Study of magnetism goes back to the observation that certain naturally occurring stones attract iron

- The two concepts were separate until 1820 with Hans Christian Oersted explained the connection between them…an electric current in a wire will affect a compass needle

Hans Christian Oersted

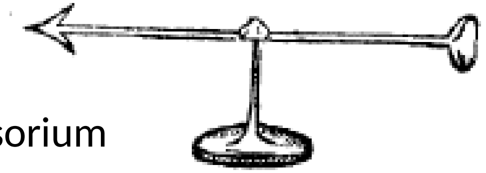
William Gilbert

William Gilbert called the property of attracting particles after being rubbed *"electricus" in 1600.*

De Magnete was a treatise of electricity and magnetism, noting a long list of elements

that could be electrified.

Gilbert invented the versorium, a device that detected statically-charged bodies



Versorium

William Gilbert

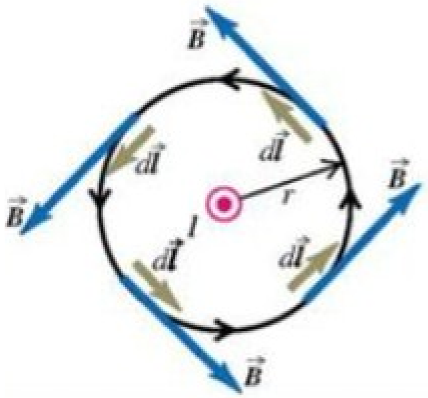
Andre Marie Ampere

Andre Marie Ampere, a French mathematician who devoted himself to the study of electricity and magnetism, was the first to explain the electro-dynamic theory.

The use of his name, Ampere, for the unit of electric current is a demonstration of his work in this field.

- **1826 – Ampere's Law**

Relates the net magnetic field along a closed loop to the electric current passing through the loop:



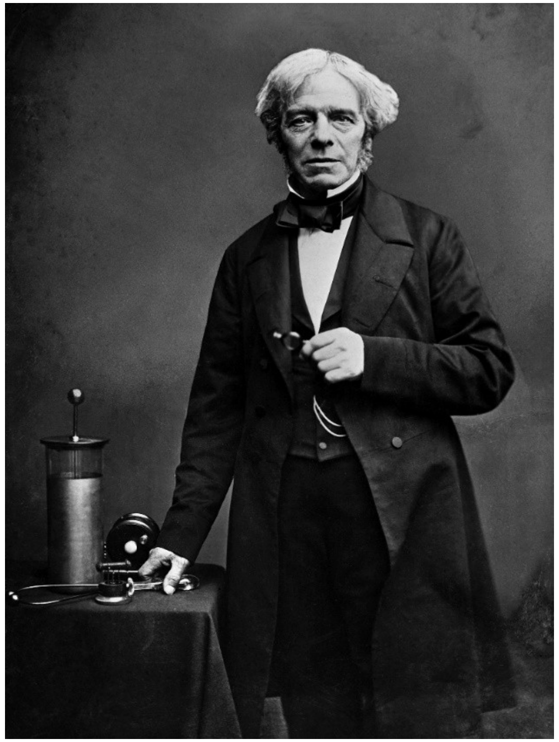
$$\oint \vec{B} \cdot \vec{ds} = \mu_0 I$$

Michael Faraday

Michael Faraday was an English scientist that actually showed a first electrical generator.

Faraday was interested in the invention of the electromagnet.

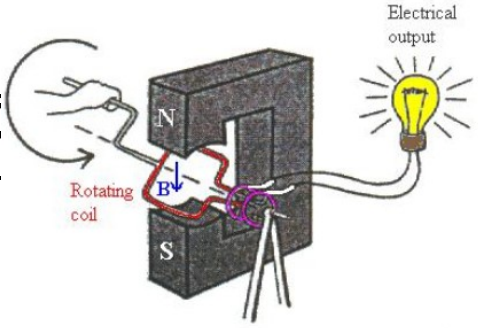
He found that if electricity could produce magnetism, why couldn't magnetism produce electricity?



- **1831 – Faraday's Law of Induction**

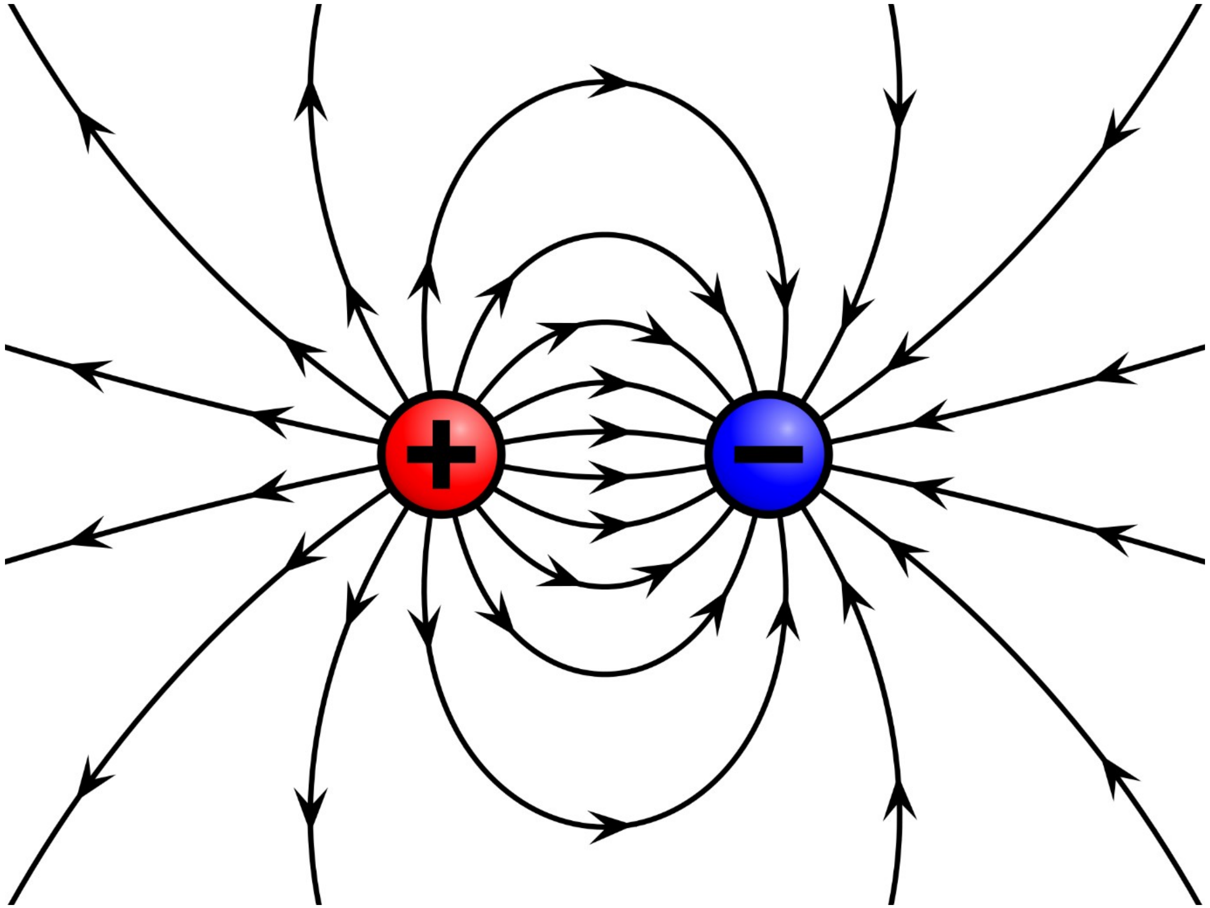
The electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path:

$$\epsilon = -\frac{d\Phi}{dt}$$

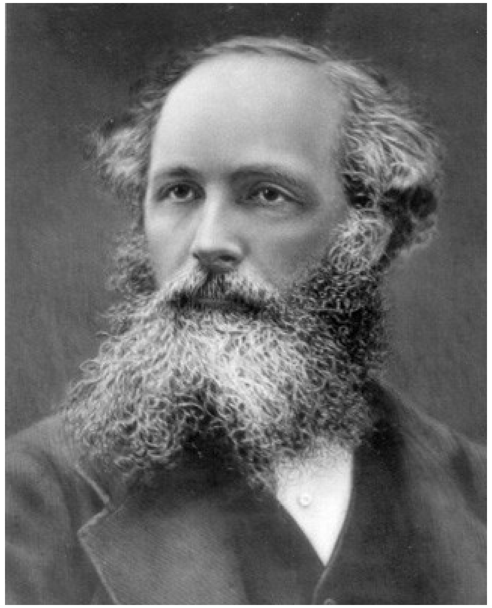


Electrical Field

At that time electric field was also discovered, by discovering that it generates an electrical force.



Historical Introduction and Current Trends



James Clerk Maxwell

1864 – Maxwell equations

A mathematical model for electric, optical, and radio technologies, such as power generation, electric motors, wireless communication, lenses, radar and so on…

Maxwell used the equations to propose that light is an electromagnetic phenomenon that propagates

Electromagnetic waves are electromagnetic energy.

Ampère's law

$$\oint \vec{H} \cdot d\vec{l} = \int_s (J_c + \frac{\partial \vec{D}}{\partial t}) \cdot d\vec{S}$$

Faraday's law

$$\oint \vec{E} \cdot d\vec{l} = \int_s (-\frac{\partial \vec{B}}{\partial T}) \cdot d\vec{S}$$

Gauss' law

$$\oint_S \vec{D} \cdot d\vec{S} = \int_v \rho dv$$

nonexistence of monopole

$$\oint_S \vec{B} \cdot d\vec{S} = 0$$

Long range WPT possible?! Only theoretically by this time…

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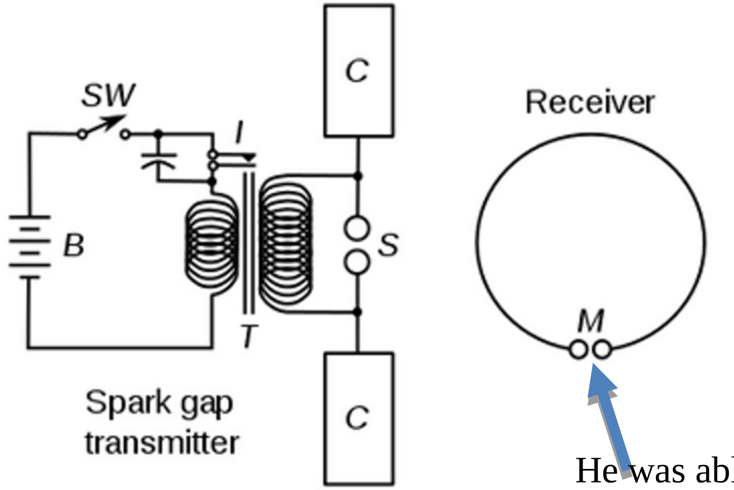
- **1884 – Poynting vector**

John Poynting describes the flow of power across an area within electromagnetic radiation which allow the analysis of wireless power transfer systems.

$$\vec{S} = \frac{1}{\mu_0}\vec{B} \times \vec{E}$$

Heinrich Hertz experience:



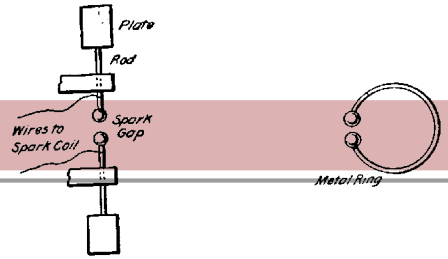
He was able to measure small sparks

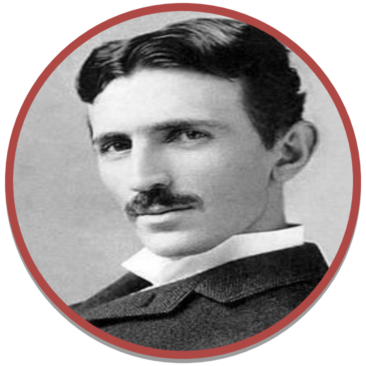
- **1888 – Evidence for radio waves**

Heinrich Hertz proved the existence of electromagnetic waves predicted by James Clerk Maxwell's equations.

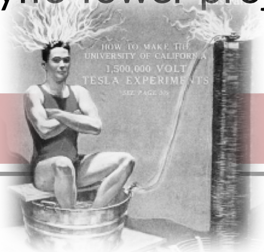
History

Hertz was a German physicist. He was the first to demonstrate the existence of electromagnetic waves by building an apparatus to produce and detect radio waves





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

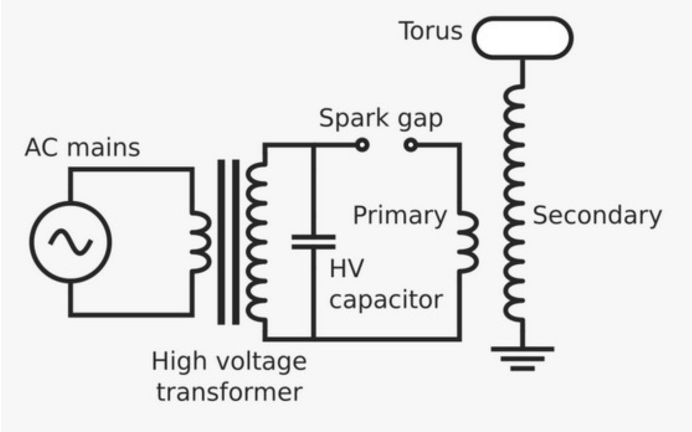


Historical Introduction and Current Trends

- **1890 – First intentional WPT experiment**

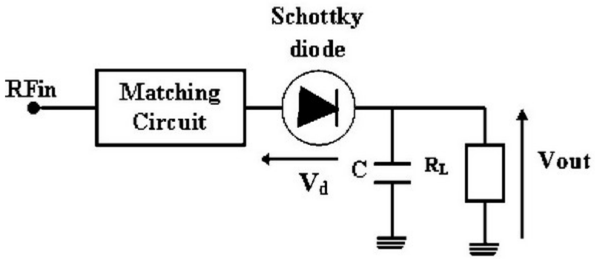
Nikola Tesla - inductive and capacitive coupling using spark-excited radio frequency resonant transformers, now called Tesla coils.

How to build a Tesla coil:

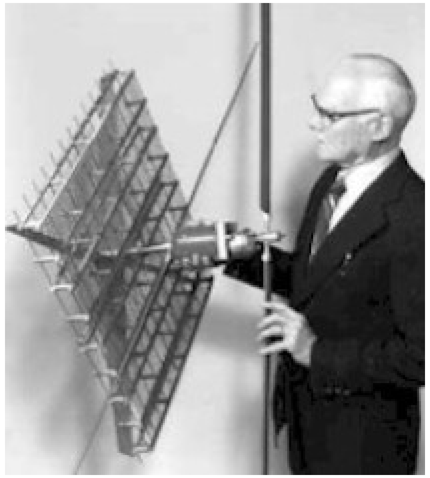


- **1960 – First Long-Range WPT experiment**

William C. Brown pioneered microwave power transmission.
Also, he invented the rectenna which could efficiently convert microwaves to DC power.



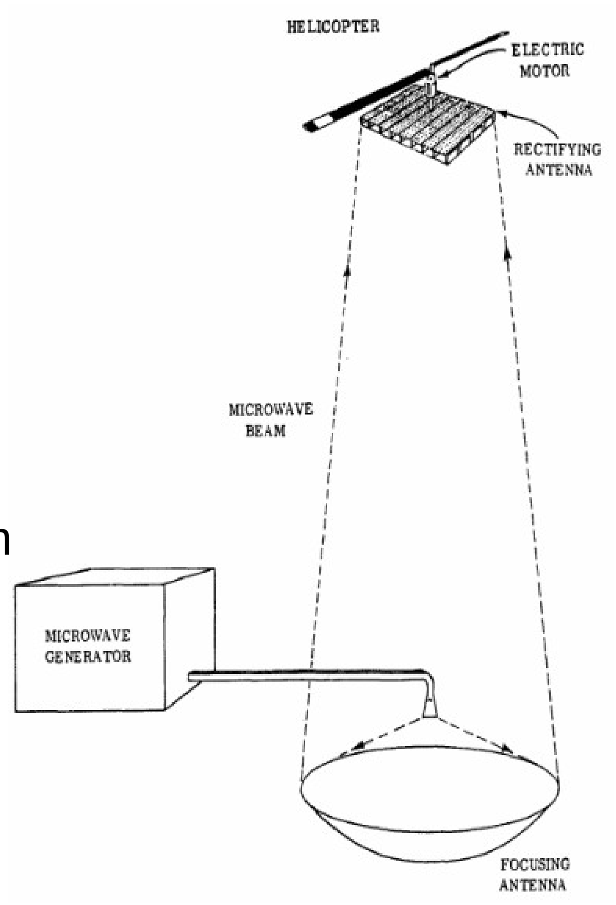
William C. Brown



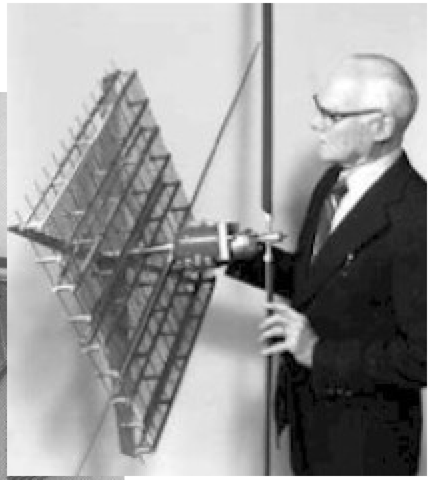
Historical Introduction and Current Trends

- **1960 – First Long-Range WPT experiment**

- Development of the Rectenna 1963
- Flying helicopter 1964
- Solar Power Satellite (SPS) 1968
- JPL Experiments 1975
- Rectenna improvement
- Venus Site Goldstone Facility 1.54 km
- SPS first serious assessment 1980



William C. Brown



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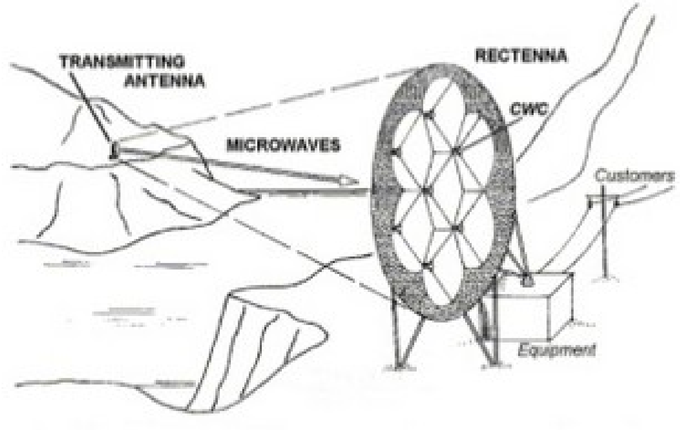
Historical Introduction and Current Trends

- **1980s**, Canada's Communications Research Centre created a small airplane that could run off power beamed from the Earth. SHARP

- **1993**, Alaska'21, provide wireless power to small rural communities

- **2001**, Grand Bassin, wireless power to the island canyon

- **2008**, Hawaii demonstration by Managed Energy Tech.. Transmission of energy over 148 km.



Historical Introduction and Current Trends

Nowadays… Internet of Things everywhere…

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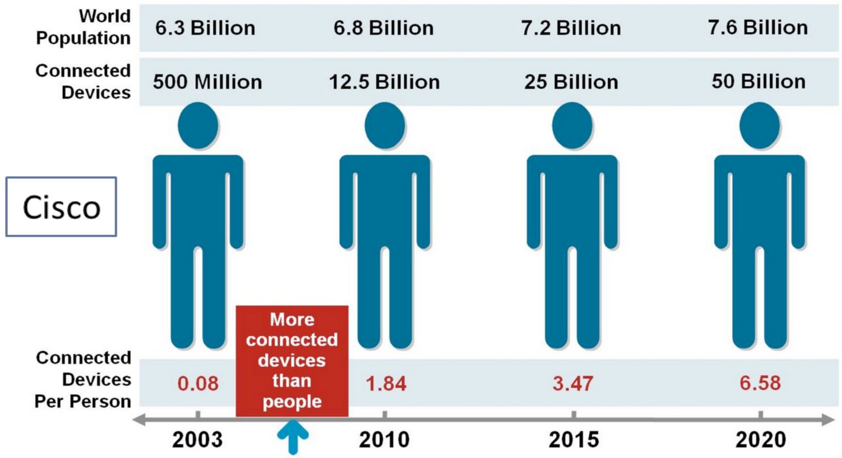
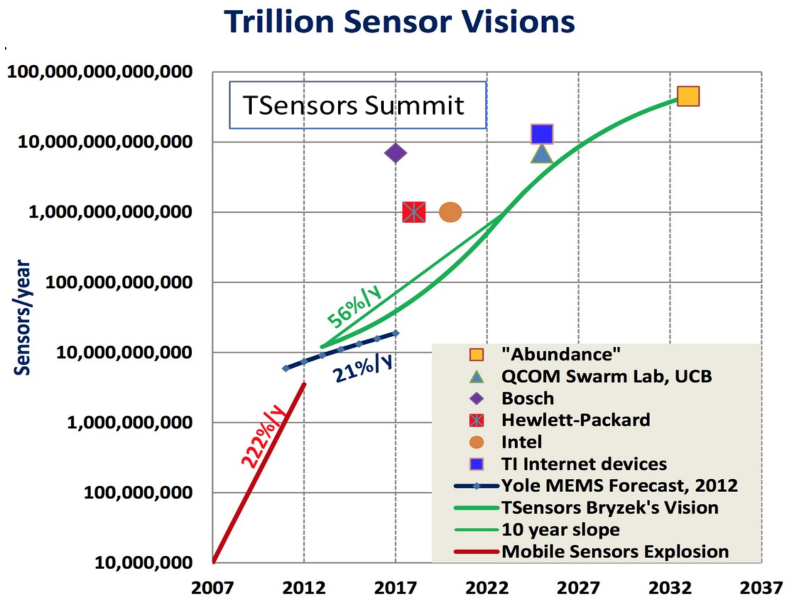
Historical Introduction and Current Trends





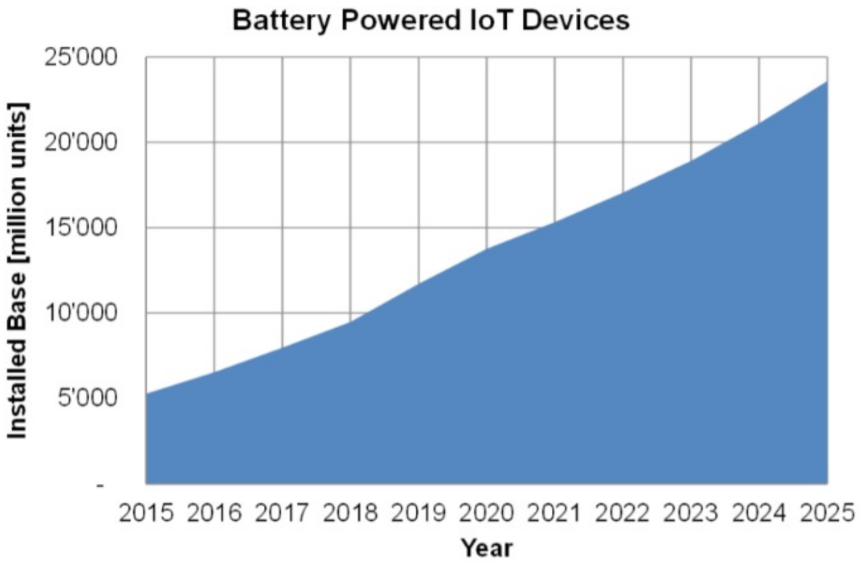
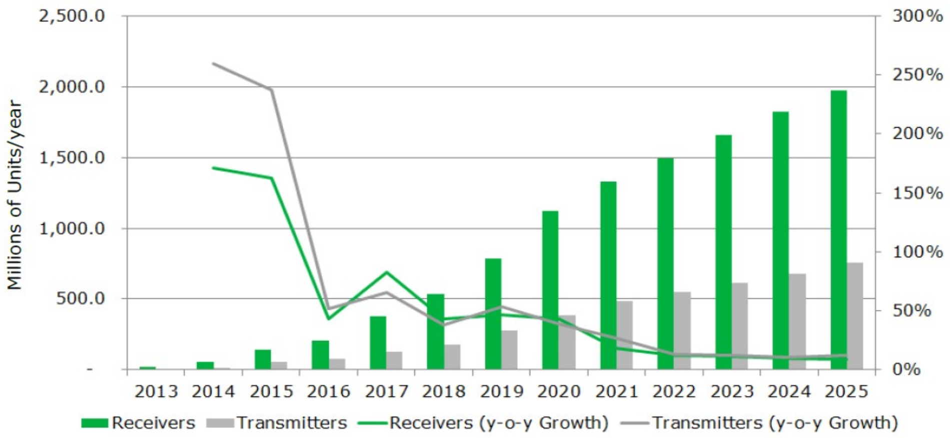
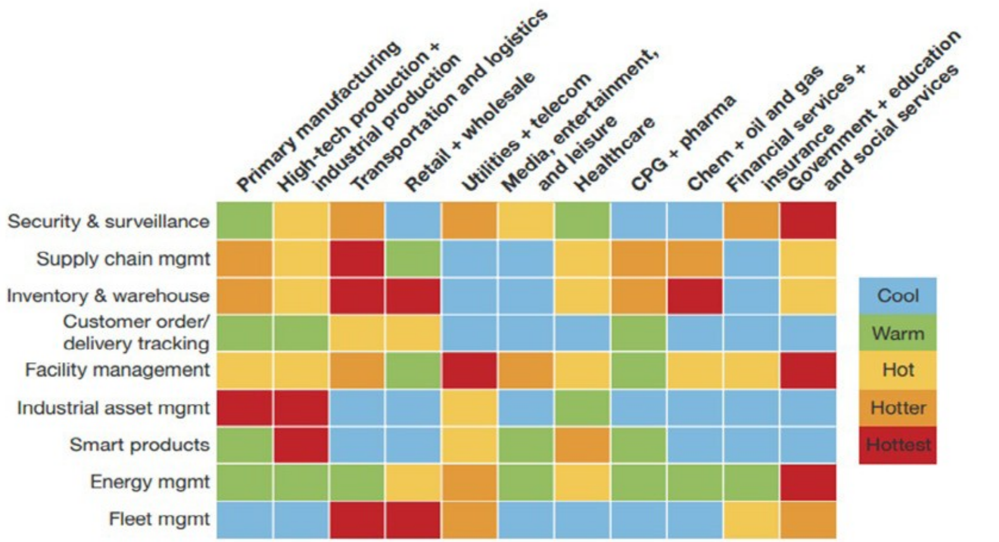


Figure taken from IEA 4E EDNA, "Energy Efficiency of the Internet of Things – technology and energy assessment report," April 2016.

Historical Introduction and Current Trends



IHS Markit, Wireless Power Market Tracker - Q1 2019

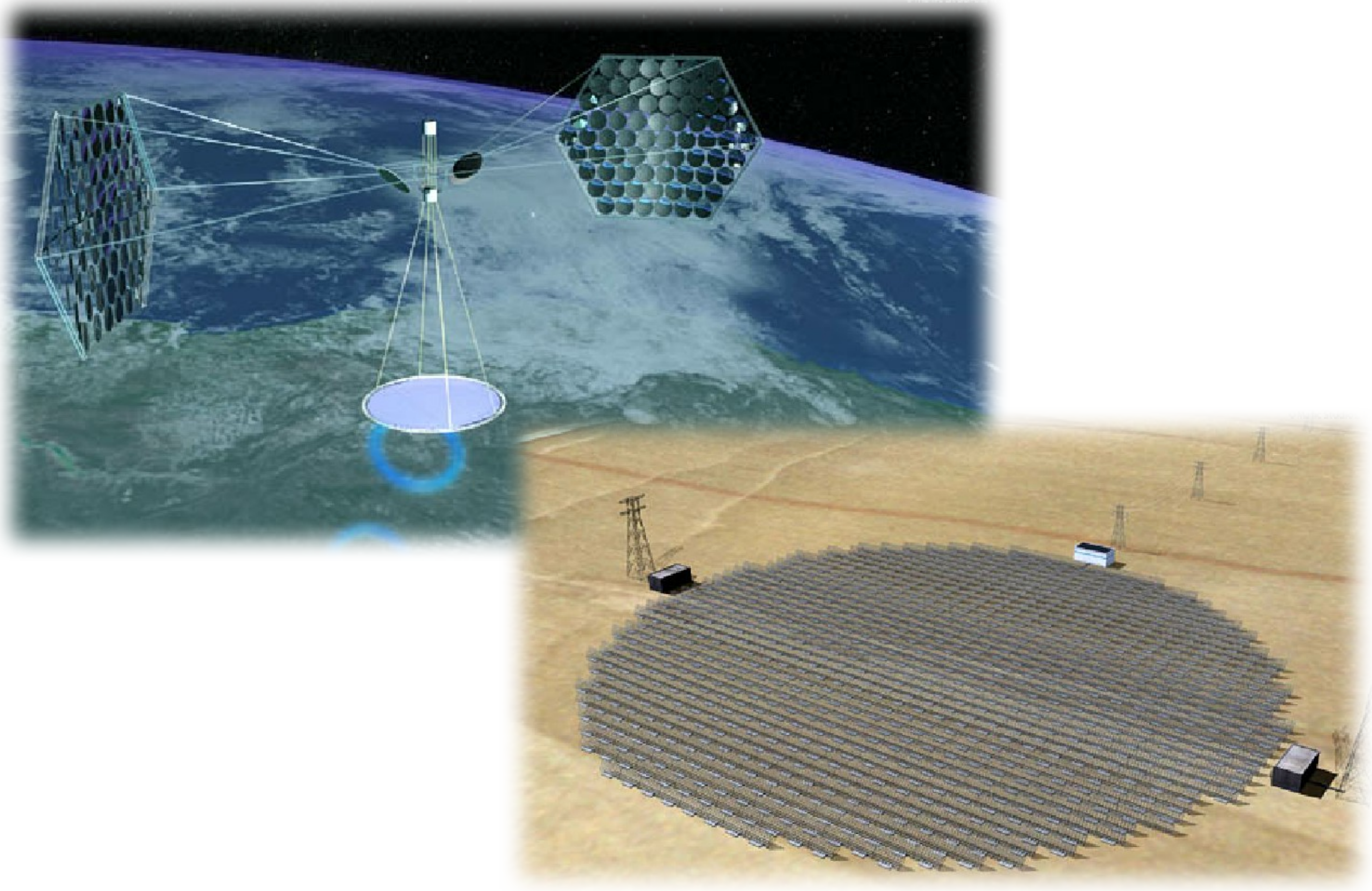


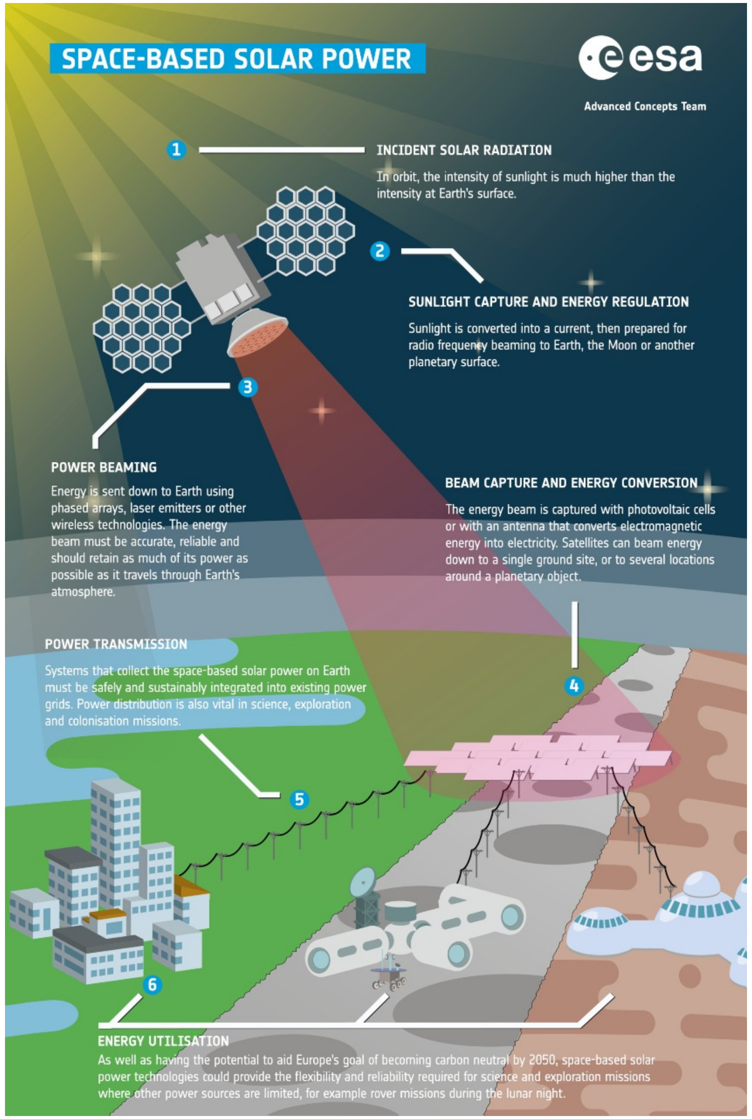
IEEE Technology Report on Wake-Up Radio: An Application, Market, and Technology Impact Analysis of Low-Power/Low-Latency 802.11 Wireless LAN Interfaces, 2017

- According to IHS Markit, the market for wireless power products keeps growing. It is expected that 2.1 billion units will be shipped worldwide by 2023.
- Additionally, the number of applications is continuously increasing.
- Some of them are still beyond our imagination.

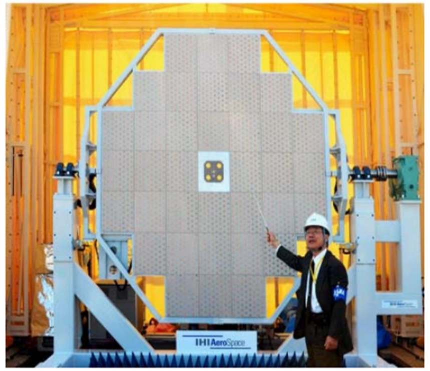
Wireless Power Transmission

Space Solar Power



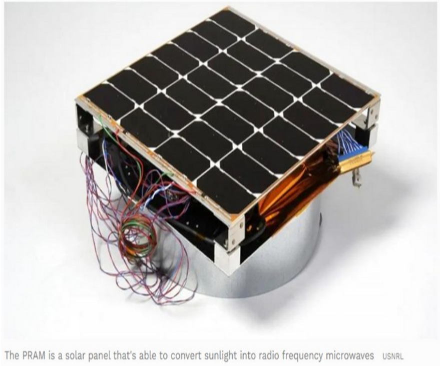


Japanese Wireless Power Demonstration 2015



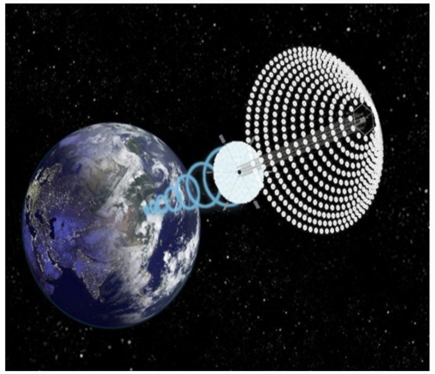
2015

JAPAN



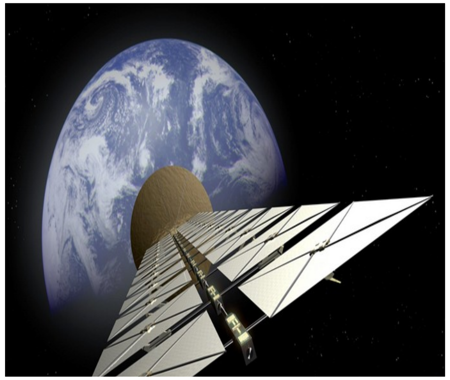
2020

NRL USA



2020

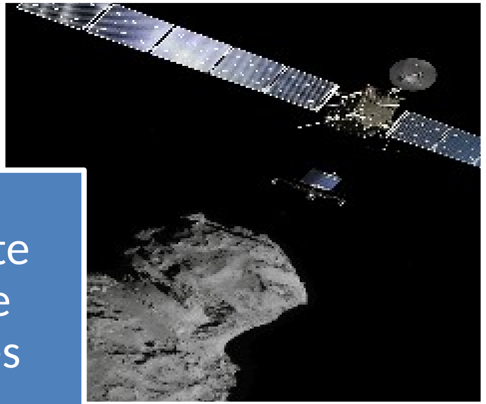
CHINA



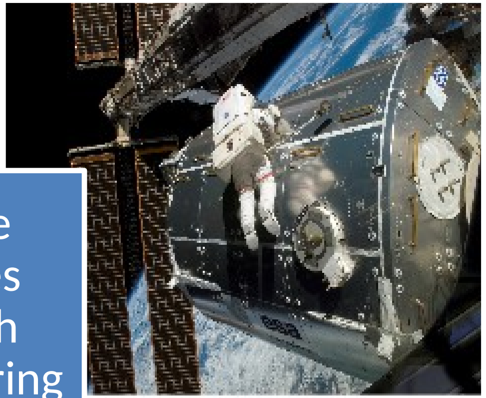
2020

EUROPE

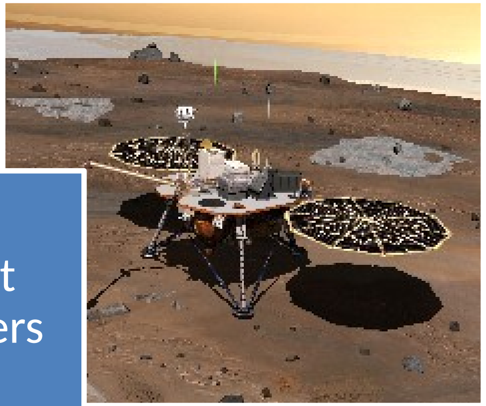
Motivation



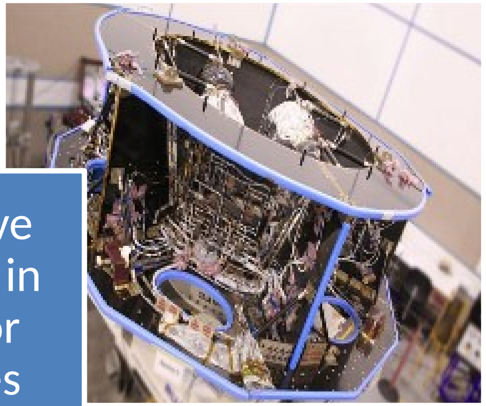
Remote Space Probes



Space Probes Health Monitoring



Planet Explorers

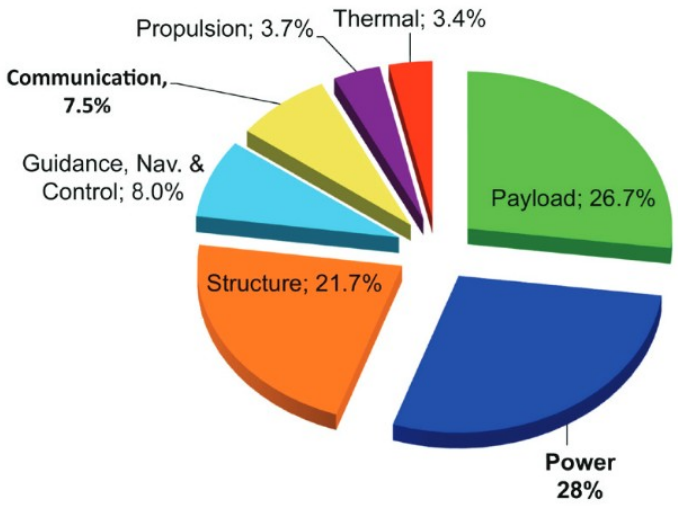


Remove Cables in Sensor Probes

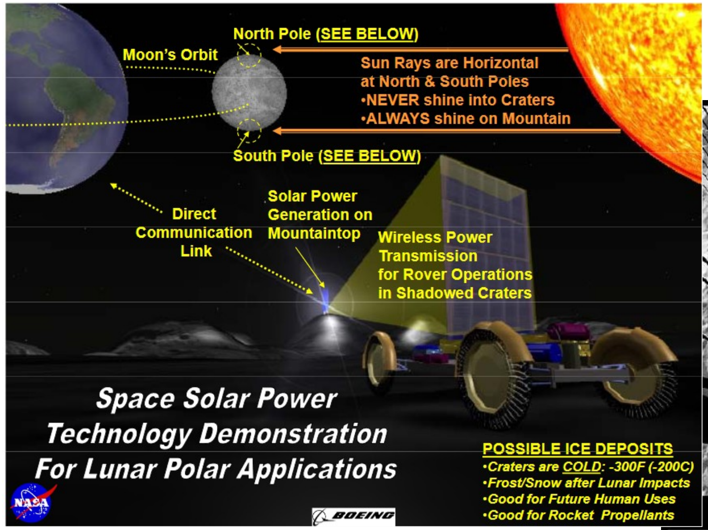
Images from NASA and ESA

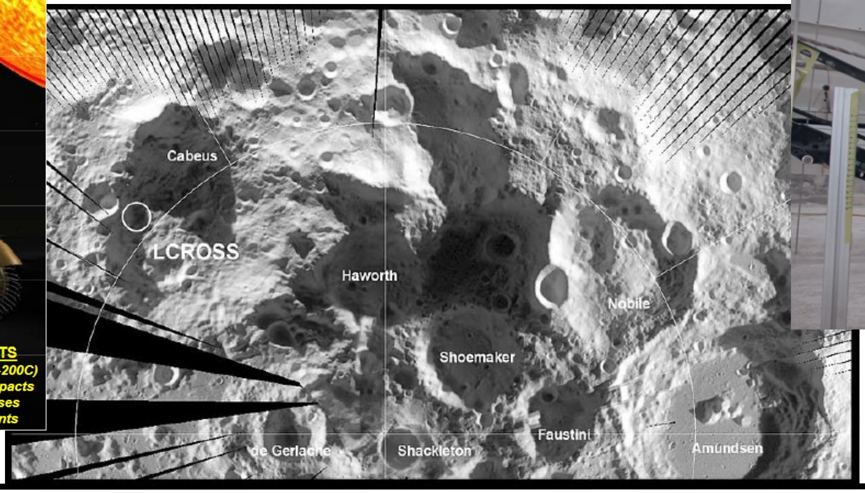
Radiative WPT in Space

- **Space exploration**
  - No living beings (as long as we know…)
  - Plenty of solar energy which can be collected, converted and transmitted to shadowed areas
  - No limits
  - Avoid batteries and cables – less mass

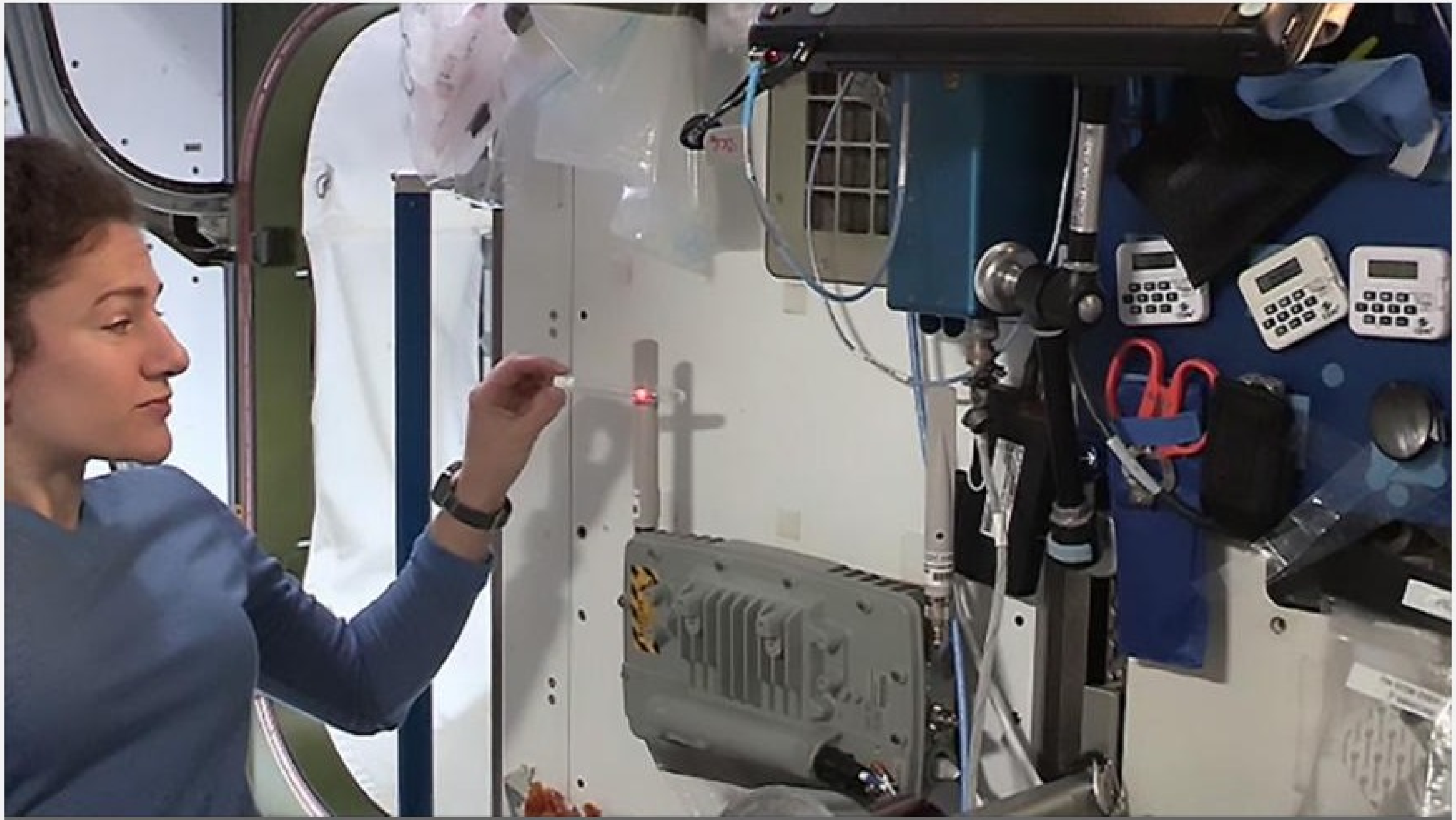


Valerie J. Lyons *et al.*, "DRAFT Space power and energy storage road map - technology area 03", National Aeronautics and Space Administration (NASA), Nov. 2010

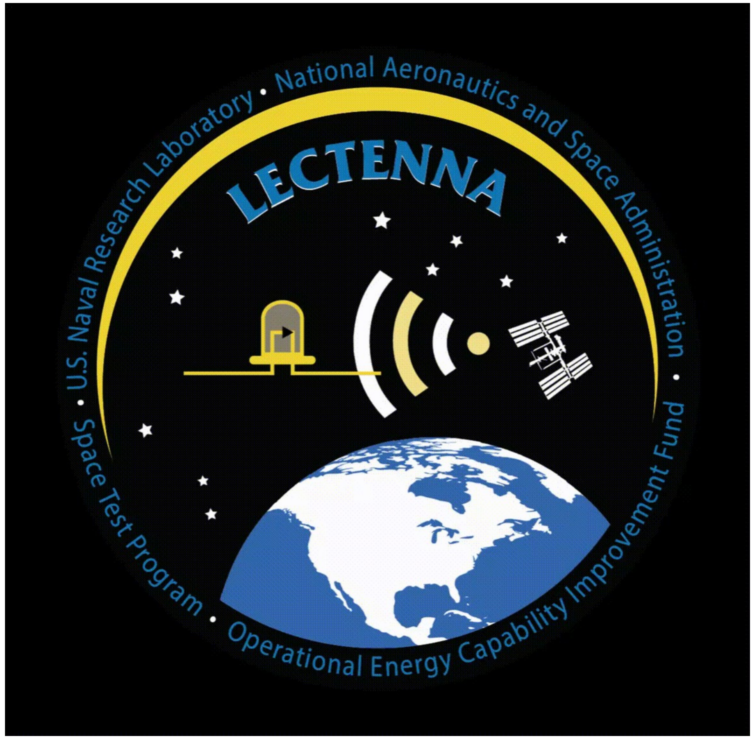




Wireless Power Transmission

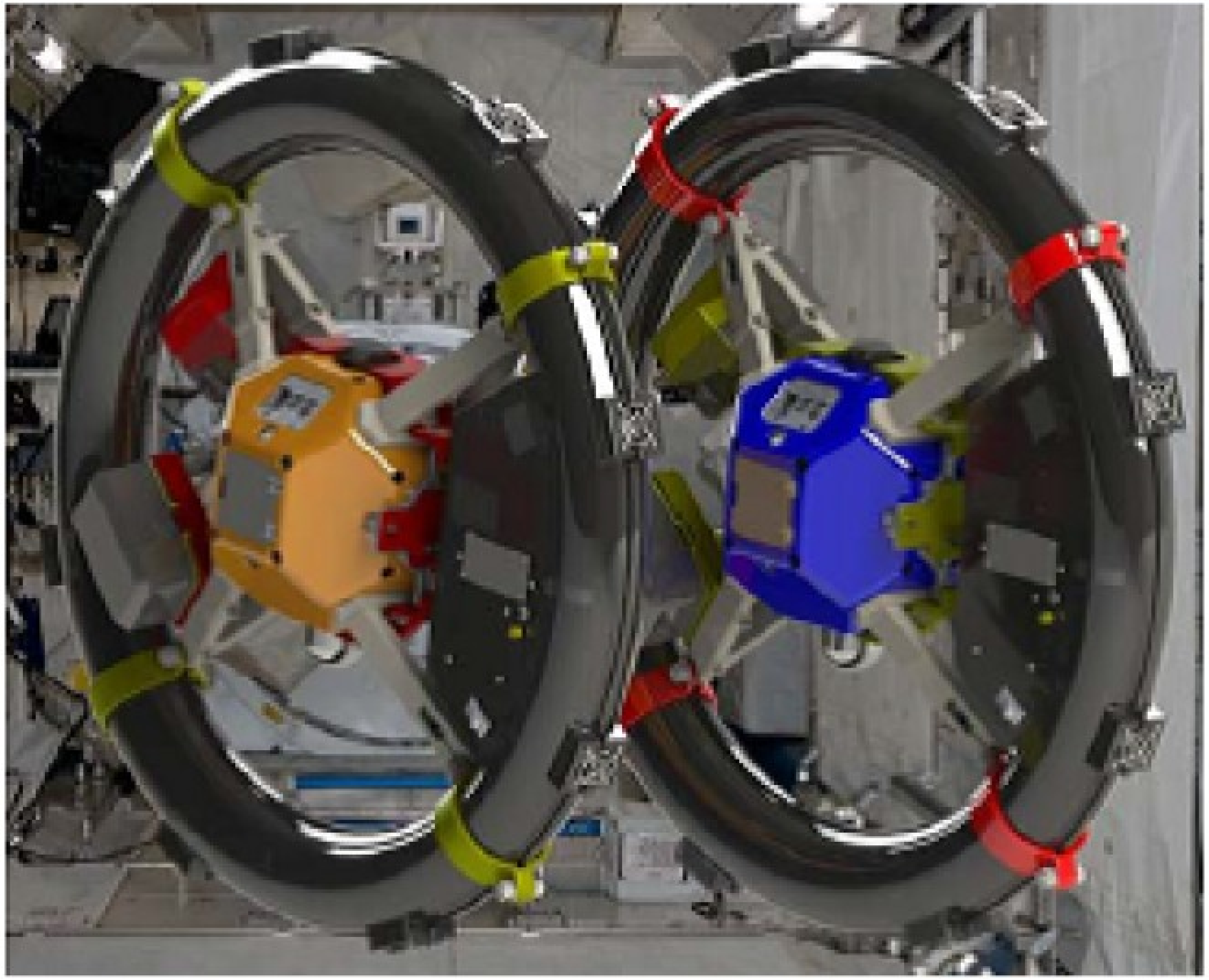


NASA astronaut Jessica Meir demonstrates how the LEctenna™, a light-emitting rectifying antenna constructed by the U.S. Naval Research Laboratory, converts electromagnetic waves into electric current on the International Space Station. Similar technology could be used on the Earth's surface to convert electromagnetic waves beamed from space-based solar arrays. Photo courtesy of NASA.



https://www.nrl.navy.mil/lectenna

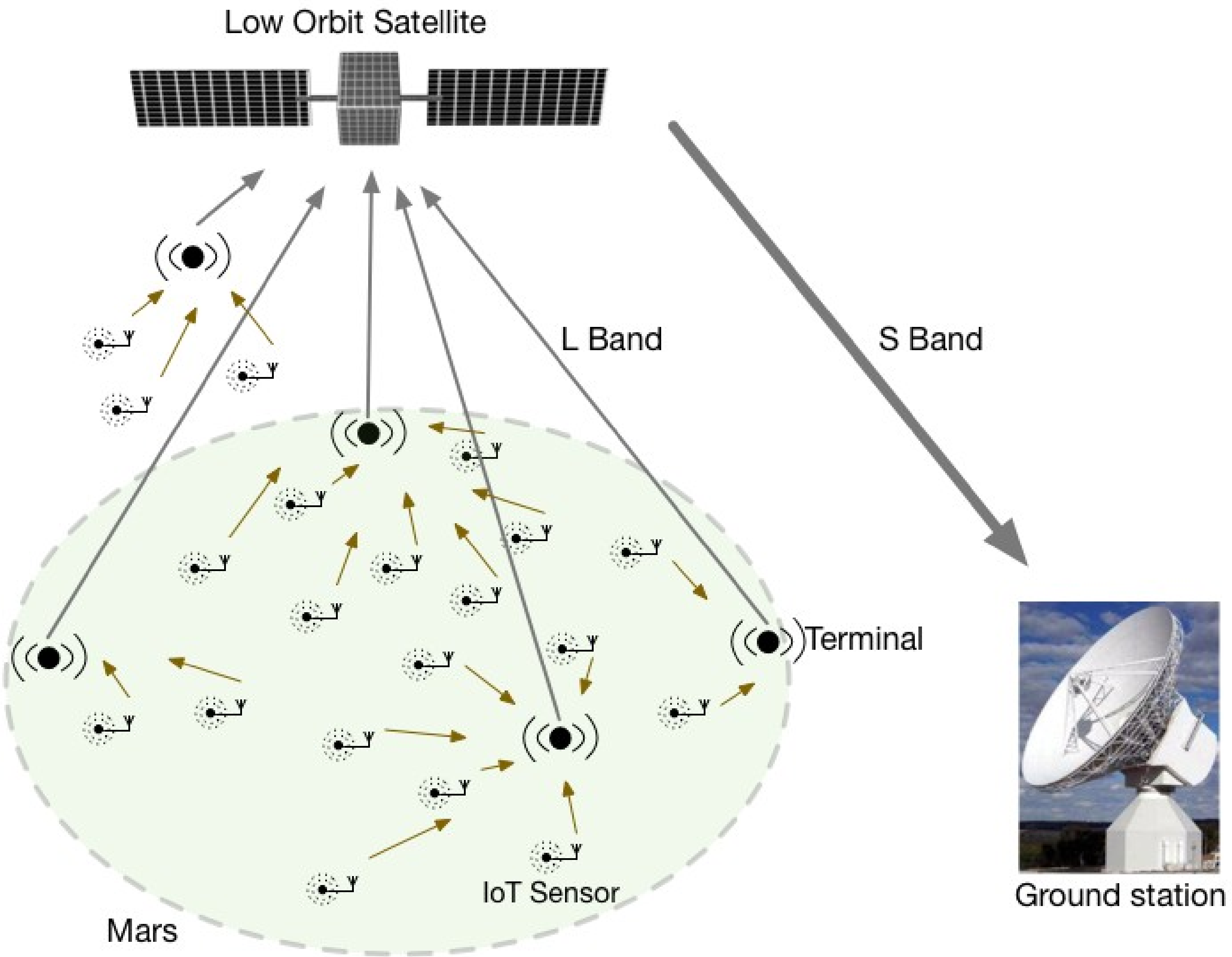
Wireless Power Transmission



RINGS

Rings is a electromagnetic based propulsion system run by MIT Space Systems Laboratory. The experiment utilizes 2 SPHERES vehicles that are places inside the RINGS support structure and interfaced together through the SPHERES expansion port via a ribbon cable. (NASA)

Developing a Deep Space Sensor IoT

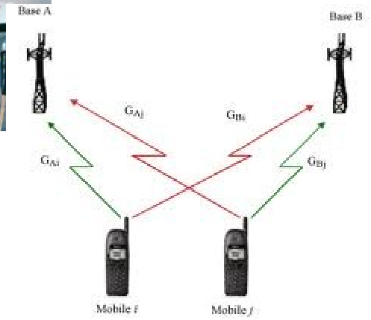


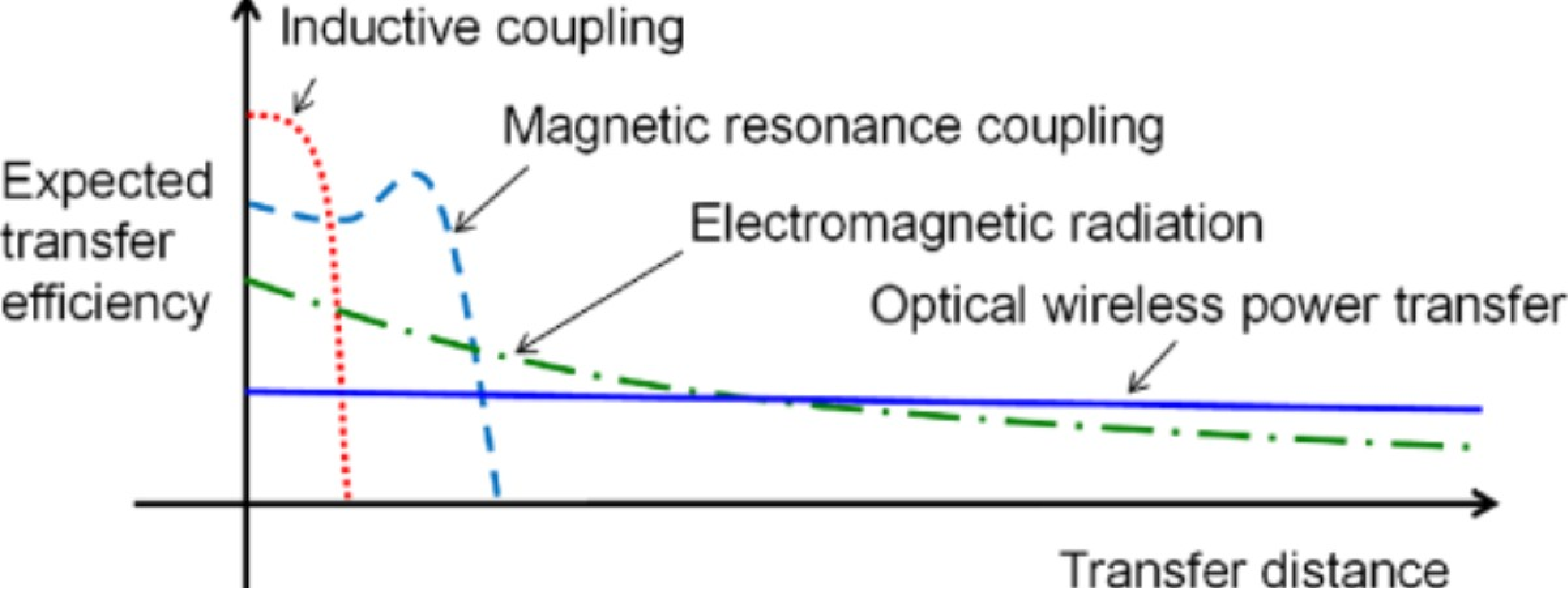
Electromagnetic (EM) Energy Harvesting Concept

- Nowadays, a huge number of wireless systems are being deployed

  Ex.: WiFi, GSM, ZigBee, LTE, Point-to-Point Links, WiMax, Broadcast Radio and TV stations

- There is a considerable amount of EM-Ambient energy
- EM Energy harvesting aims to collect the EM-ambient energy from the medium and convert it into DC "electricit



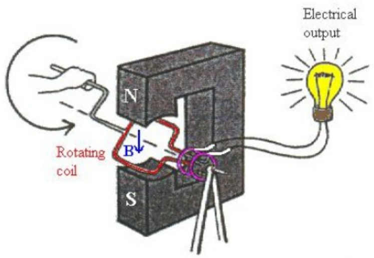


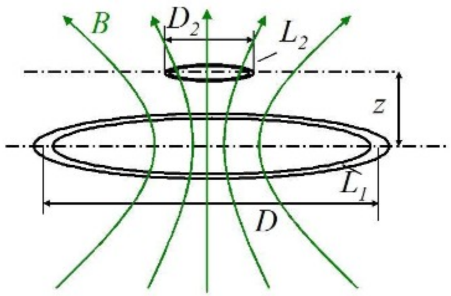
2. Types of WPT

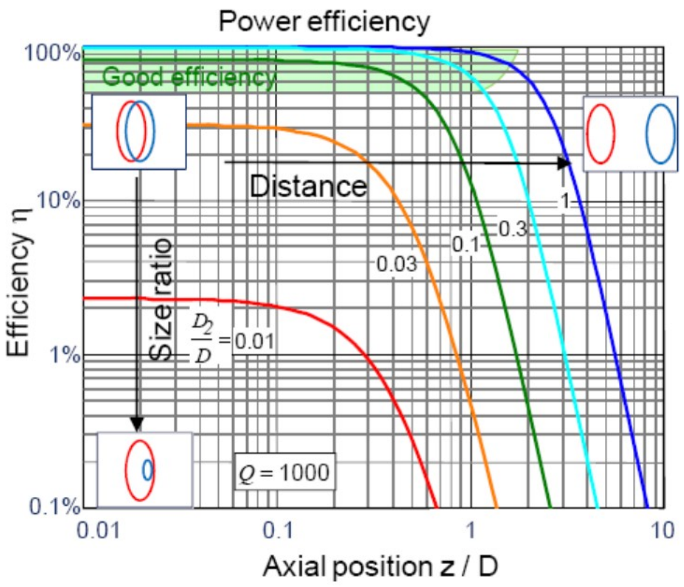
i. Inductive Coupling
ii. Radiative Near-Field
iii. Radiative Far-Field

Inductive (Resonant) Coupling

Faraday's Law of Induction







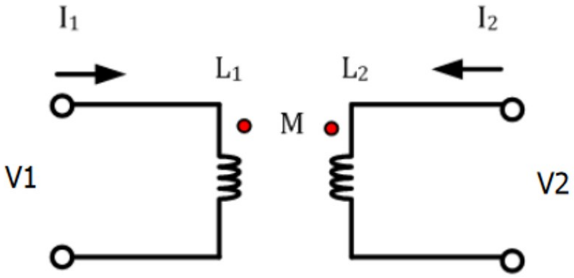
- **Coupling between coils**

  Distance between coils
  Ratio of diameters of the two coils
  Alignment

- **Quality Factor**

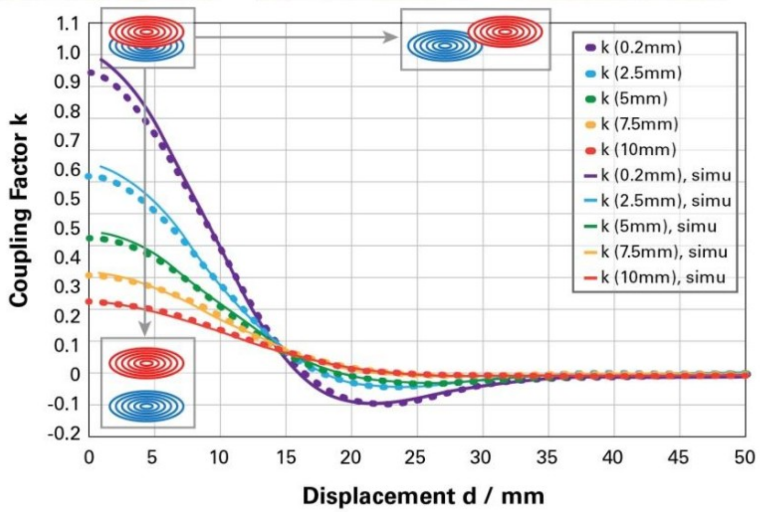
  Ratio of inductance to resistance
  Geometric mean of the two Q factors

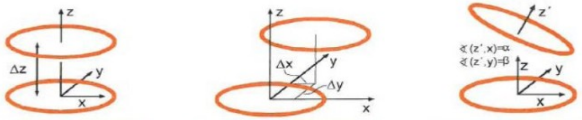
- **TX "sees" RX and vice-versa**



$$V_1 = L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} = (j\omega L_1) I_1 + (j\omega M) I_2$$

$$V_2 = M \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} = (j\omega M) I_1 + (j\omega L_2) I_2$$

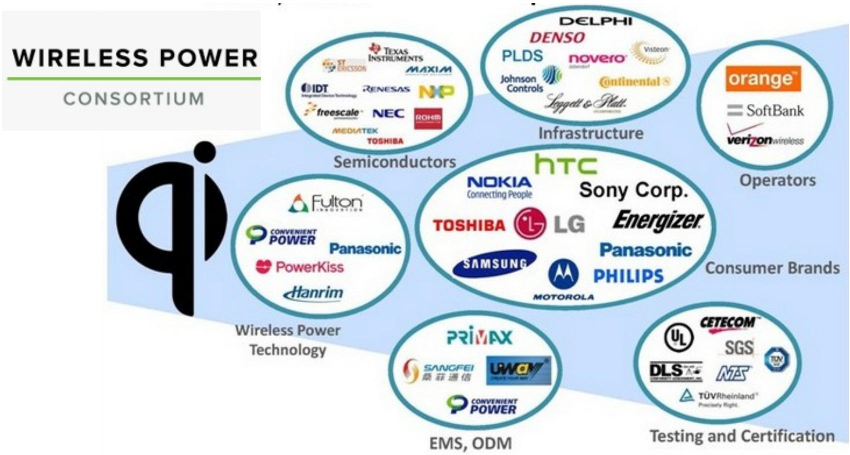


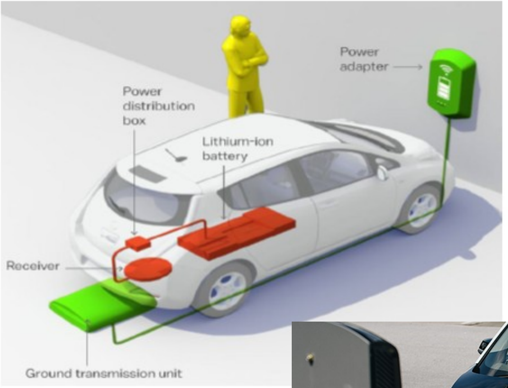


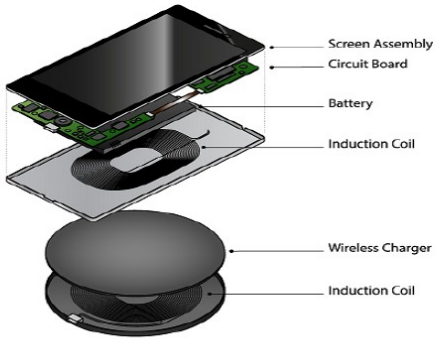
Dave Wilson, WPC1701 Qi Developer Forum - Circuit Design Considerations

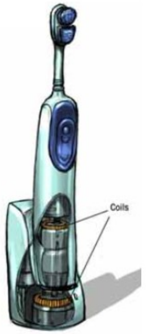
Inductive (Resonant) Coupling

- Nowadays, several inductive WPT systems are commercially available for several daily applications;
- Resonant inductive coupling is a special case of inductive coupling
- Radio Frequency Identification (RFID);
- Cellphone charging..







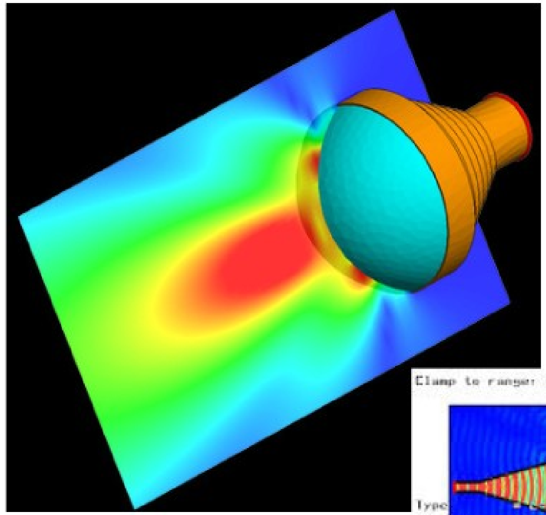


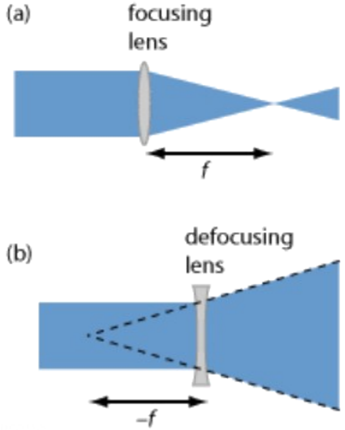
Radiative Near-Field

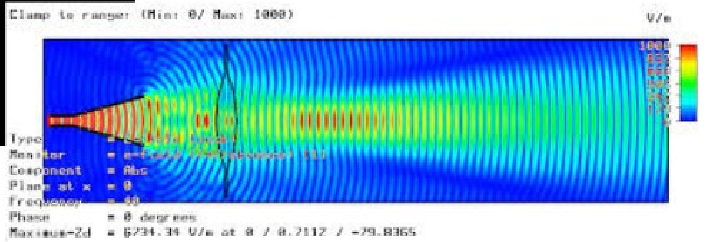
- Allows to increase the electromagnetic power density in a size-limited spot region close to the antenna/array aperture

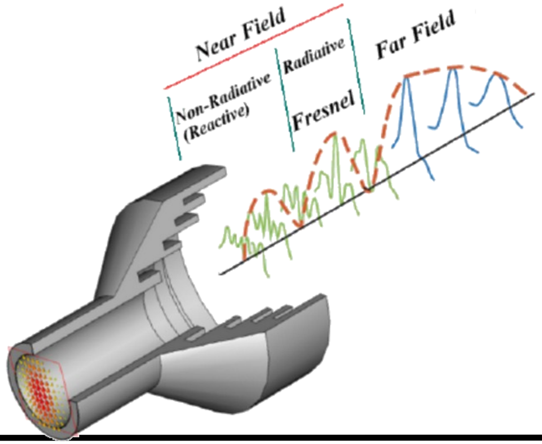
- Large antenna apertures required for short focusing distances

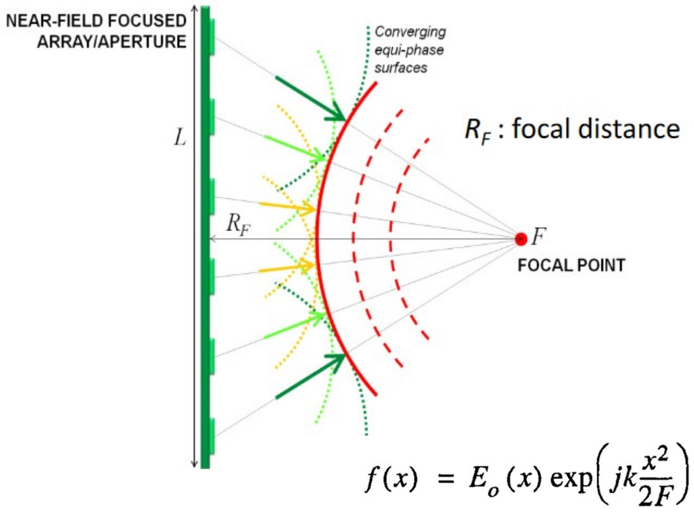
- High transmission efficiency



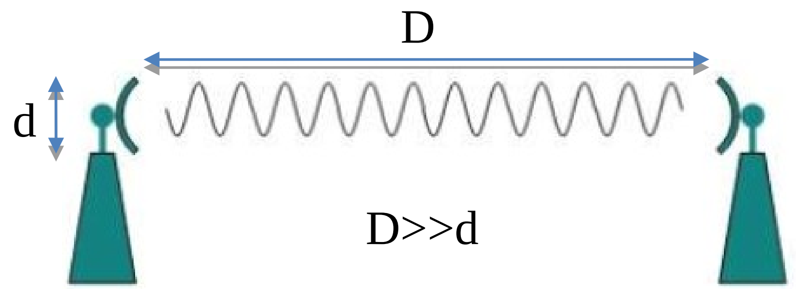


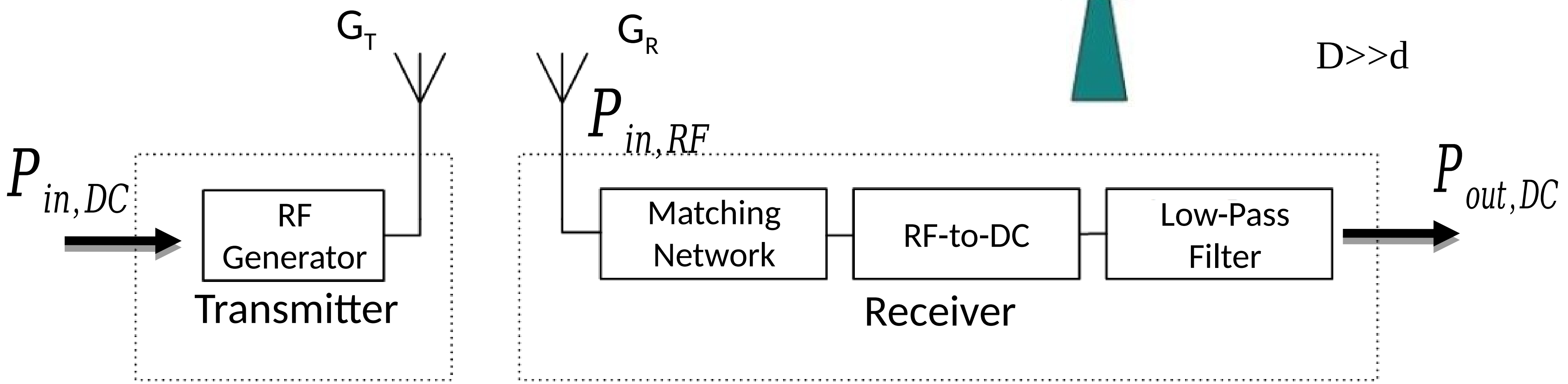






Radiative Near-Field





- Raise the transmitted power
- Boost RF-to-DC conversion efficiency
- Optimize the transmitter
- High directional antennas

$$\eta = \frac{P_{out,DC}}{P_{in,DC}}$$

Radiative Near-Field

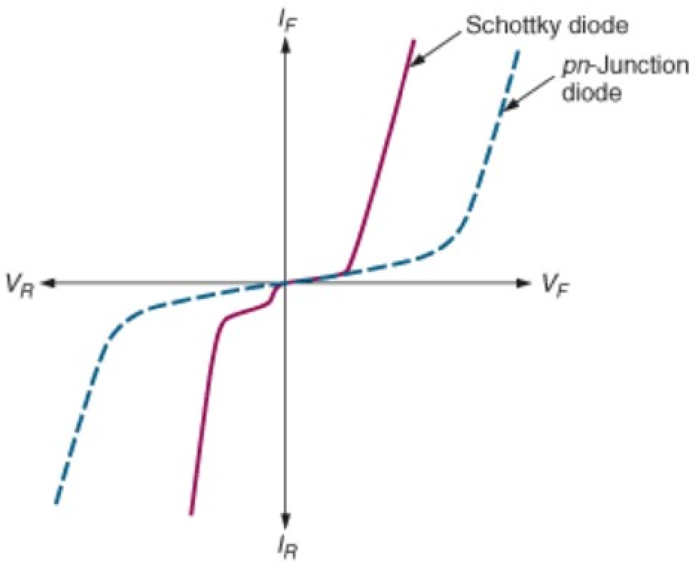
- Electronic devices require DC energy to operate;
- Although, some devices such as motors and incandescent bulbs may run at AC voltages; Nikola Tesla lit incandescence bulbs without any conversion…
- DC is storable in batteries while AC is not;

- Similarly, a WPT receiving device must convert the received RF (or AC) energy into usable DC energy.

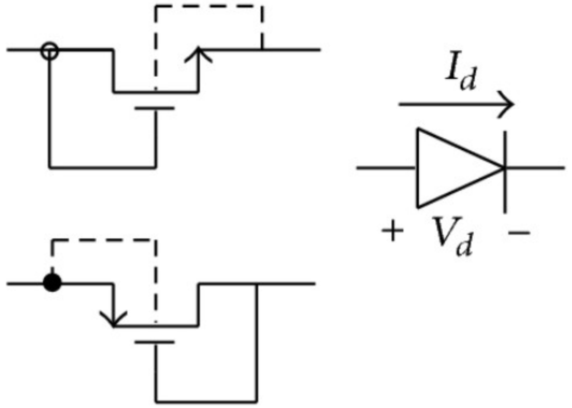
Radiative Far-Field

All types of WPT must employ rectifying elements:

- **Schottky diodes**
  - Metal-semiconductor junction results on a low threshold voltage and a low junction capacitance

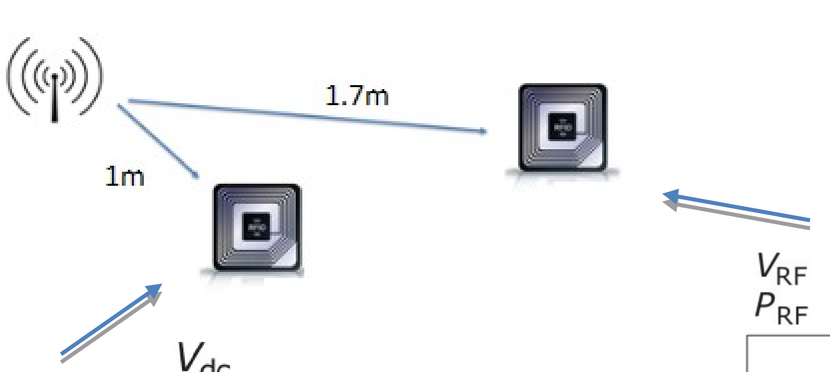


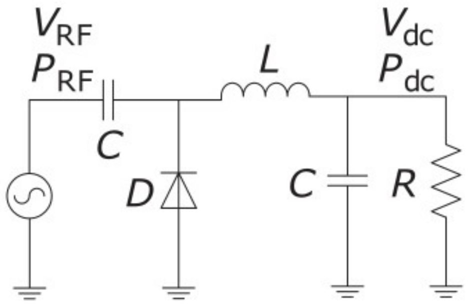
- **Diode-connected transistors**
  - Digital logic can be designed within the same integrated circuit;
  - Lower parasitic values;
  - Low cost;
  - Widely used in RFID.

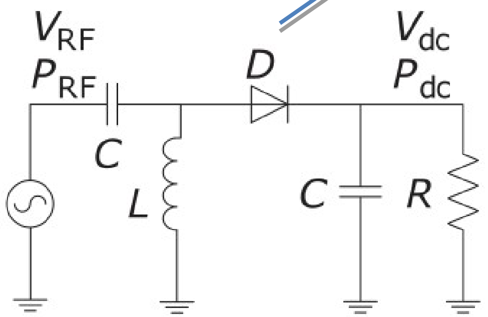


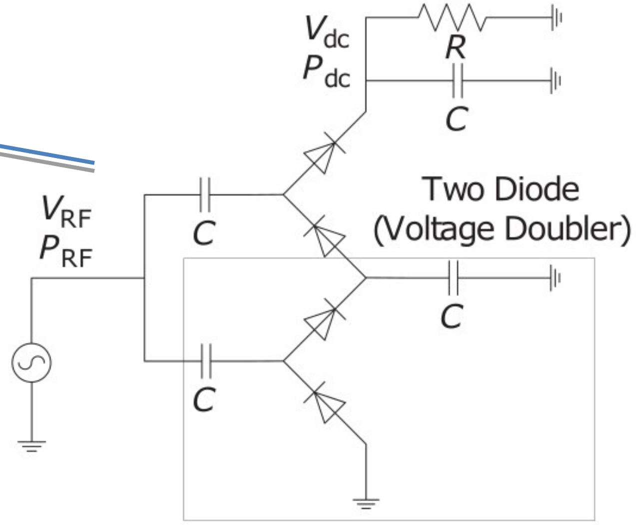
Radiative Far-Field

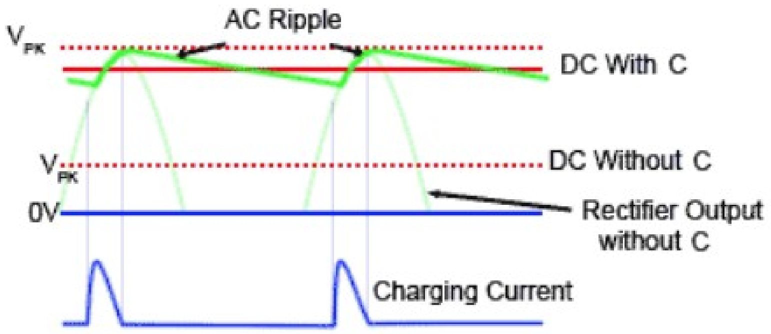
- **Most used examples:**

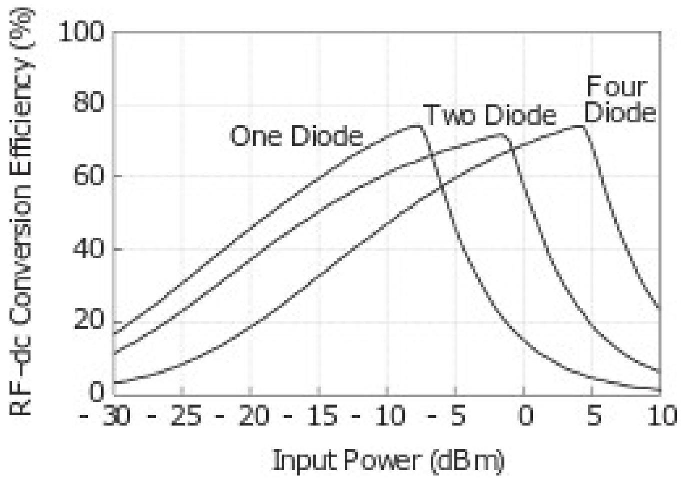












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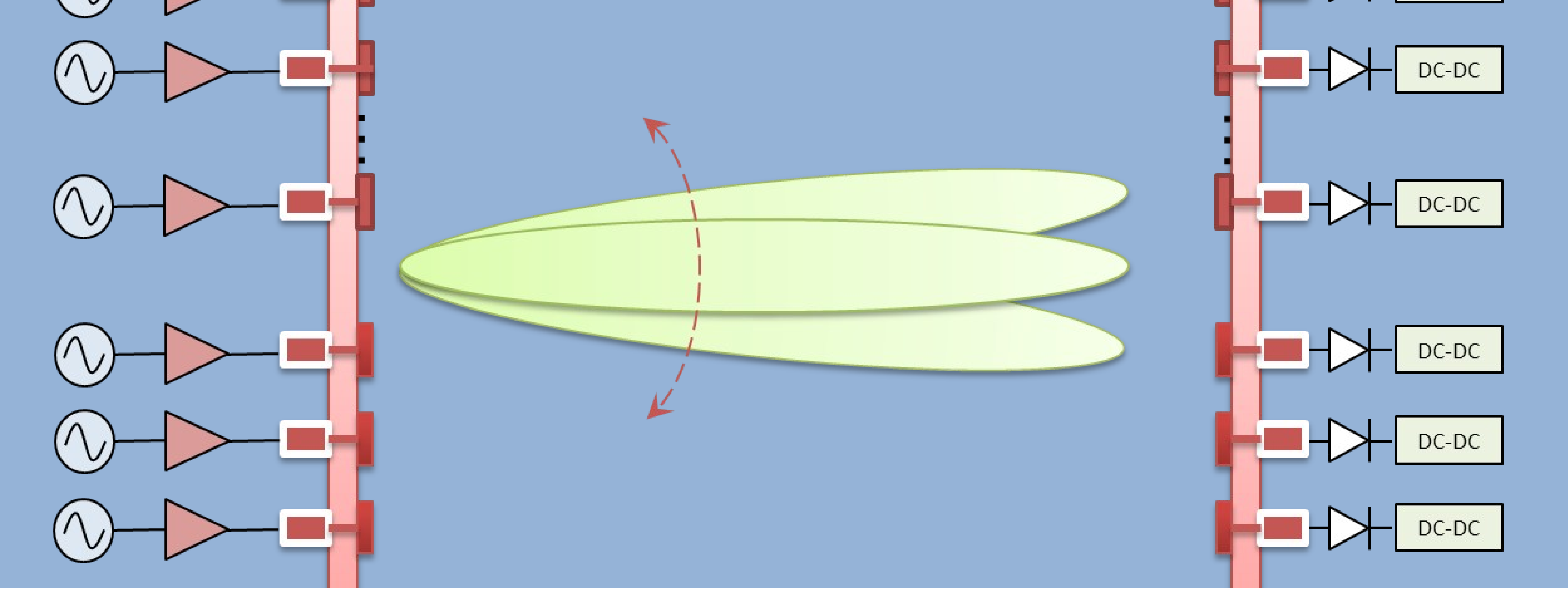
Radiative Far-Field

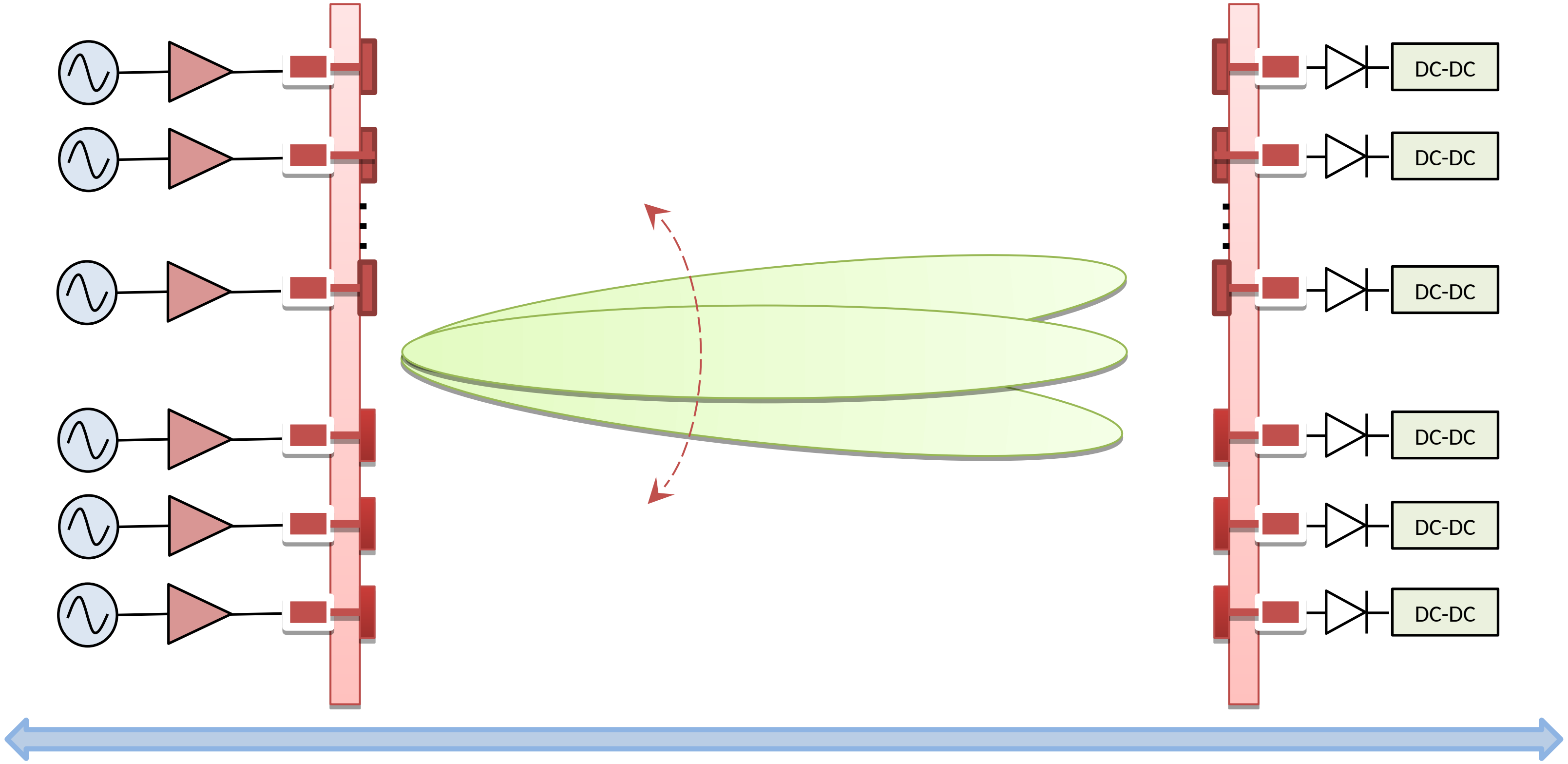
Potential applications…

…some are a reality already!



Design of a WPT Link

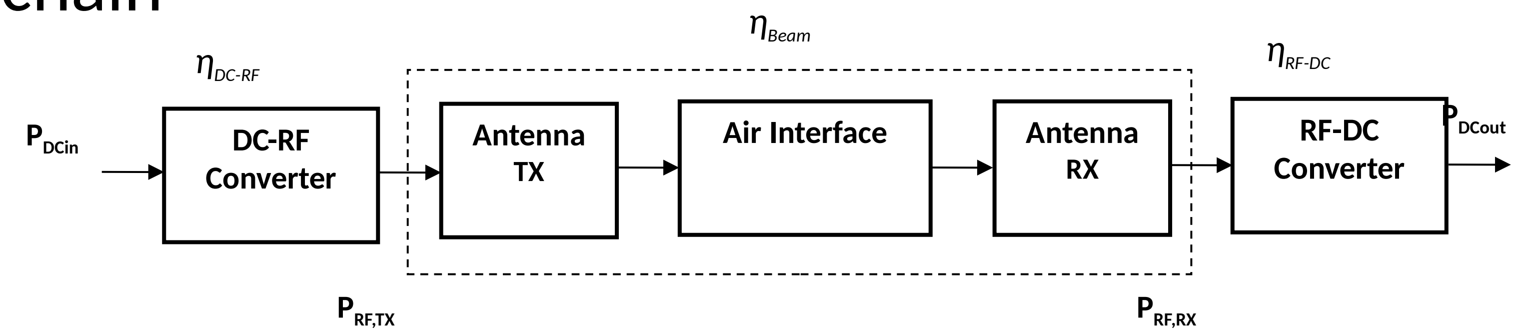
General Concepts



DC-RF 70% | RF-RF 50% | RF-RF 80% | RF-RF $\left(\frac{\lambda}{4\pi r}\right)^2$ | RF-RF 80% | RF-DC 70% | DC-DC 90%

Design of a WPT Link

Typical WPT chain

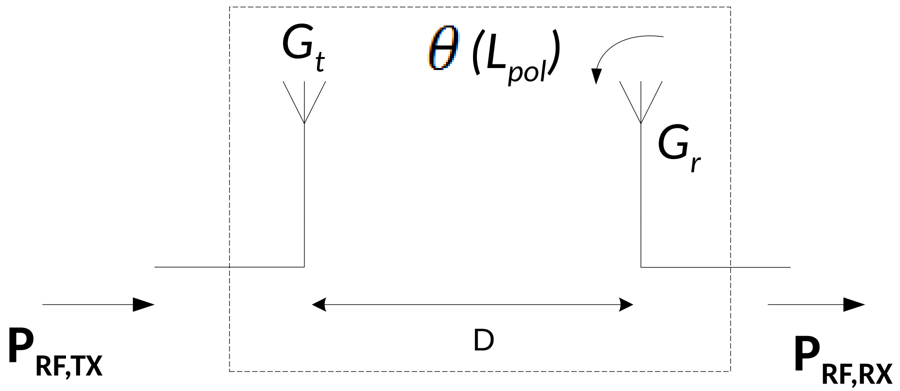


$$\eta_{Total} = \frac{P_{DCout}}{P_{DCin}} = \eta_{DC-RF} \cdot \eta_{Beam} \cdot \eta_{RF-DC}$$

- In Electromagnetic Energy Harvesting we only can control the beaming efficiency and the RF-DC efficiency

Design of a WPT Link

The beaming efficiency: comprises antenna gains, free-space loss and polarization loss due to misalignment between antennas



$$\eta_{Beam} = \frac{P_{RF,RX}}{P_{RF,TX}} = G_t G_r \left(\frac{\lambda}{4\pi D}\right)^2 L_{pol}$$

$$L_{pol} = \cos^2\theta$$

- θ - is the polarization angle between the two antenna s
- Dual-polarized antennas alleviate the dependency on the Polarization angle

General Concepts

DC-RF

RF-RF

$$\left(\frac{\lambda}{4\pi r}\right)^2$$

RF-RF

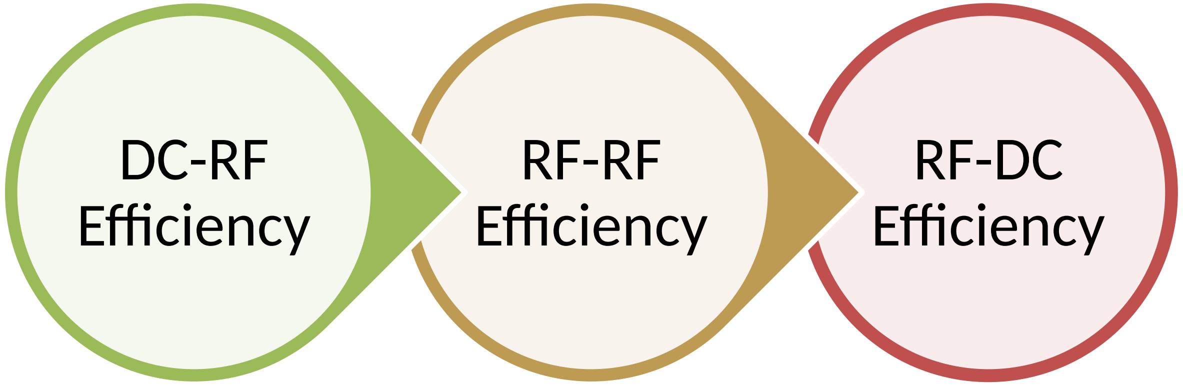
RF-DC

DC-DC

WPT				
Frequency [GHz]	2	5	10	18
Wavelength [m]	0,15	0,06	0,03	0,017
RF-DC Conversion				
DC-RF Efficiency [%]	80	75	65	60
DC Power in Transmmmiter [W]	100	100	100	100
Amplifier Gain [dB]	30	30	30	30
RF-RF Efficiency [%]	70	60	40	30
Antenna Feed Power [W]	56	45	26	18
Beam Efficiency				
Antenna gain [dB]	20,0	20,0	20,0	20,0
Distance [m]	2	2	2	2
Free Space Atennuation	3,56E-05	5,70E-06	1,42E-06	4,40E-07
Receive Antenna [dB]	20,0	20,0	20,0	20,0
Beam Efficiency [%]	0,36	0,06	0,01	0,00
Received RF power [W]	19,95	2,56	0,37	0,08
DC-RF Conversion				
RF-DC Efficiency [%]	80	75	70	60
DC power [W]	15,96	1,92	0,26	0,05
DC-DC Efficiency				
DC-DC Efficiency [%]	**15,96%**	**1,92%**	**0,26%**	**0,05%**

General Concepts

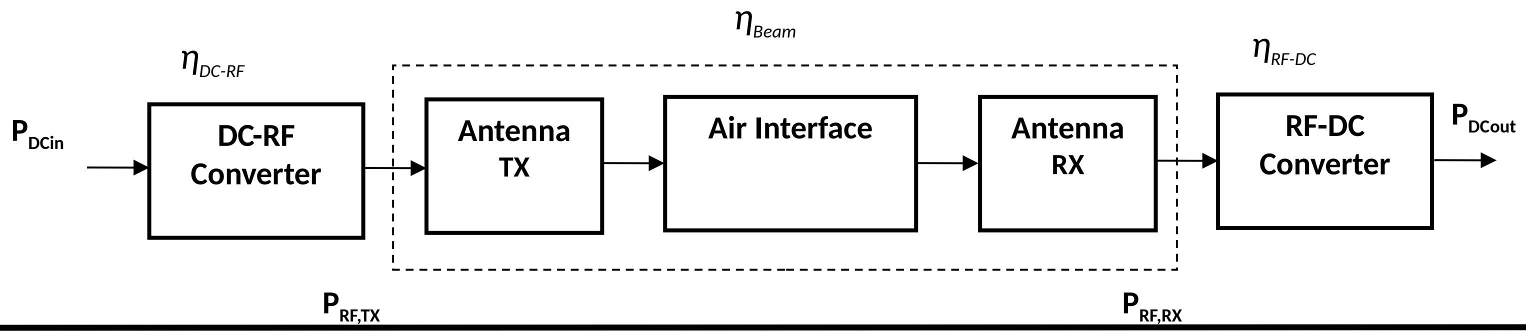
$$\left(\frac{\lambda}{4\pi r}\right)^2$$



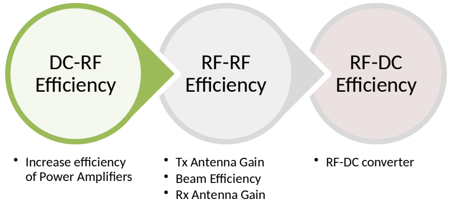
- Increase efficiency of Power Amplifiers

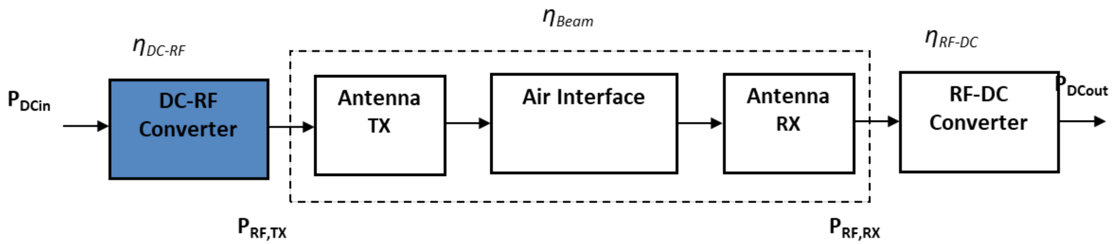
- Tx Antenna Gain
- Beam Efficiency
- Rx Antenna Gain

- RF-DC converter

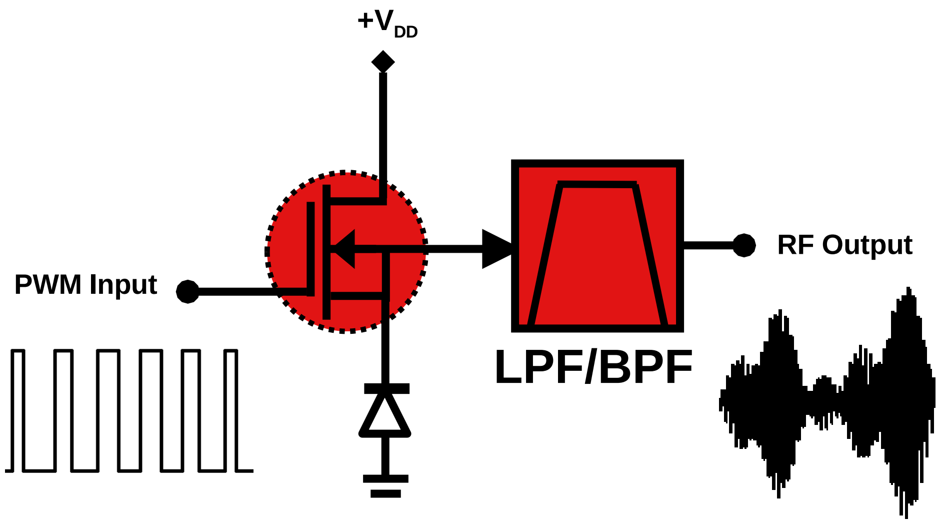


DC-RF Conversion

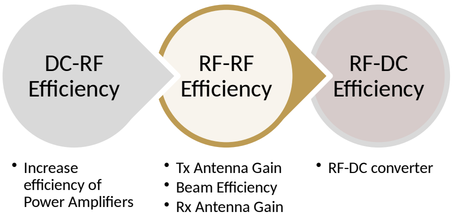


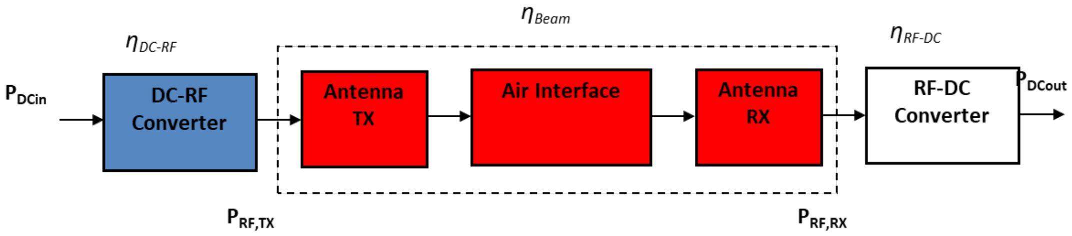


CMOS type PA using switch PA approaches

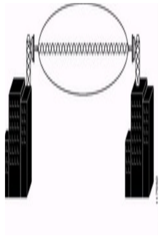


RF-RF Conversion

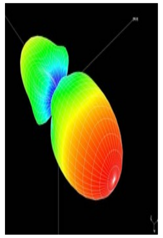




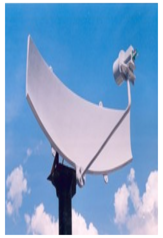
Design of very high beam efficiency antennas



Optimize antenna size and beam control in order to guarantee an Fresnel zone operation!!



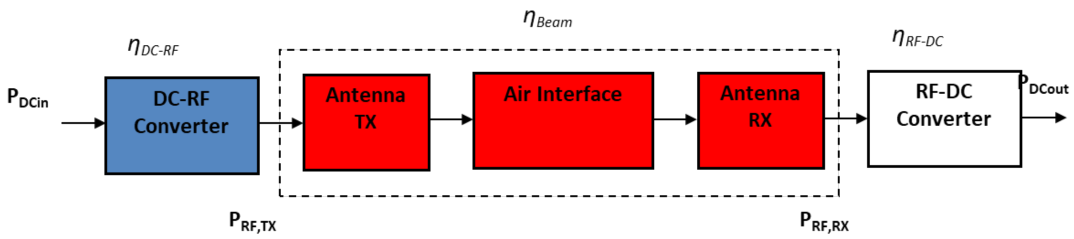
Design Gaussian Beam Antenna Arrays

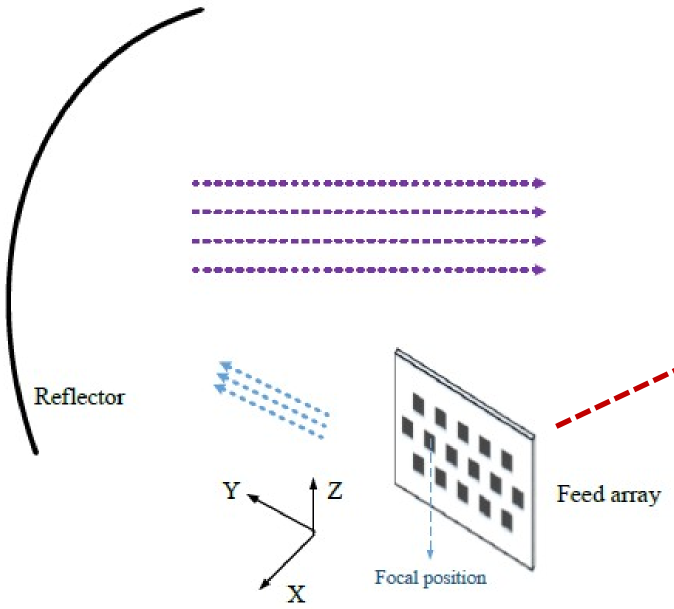


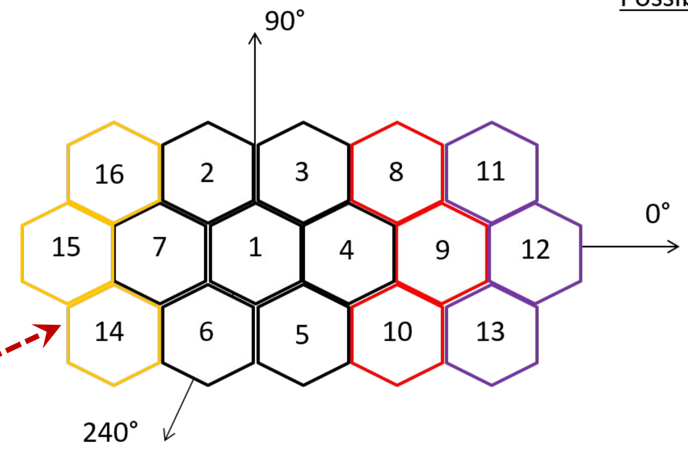
Optimize reflector based antennas

Improved Antenna Arrays

Active Antenna Arrays



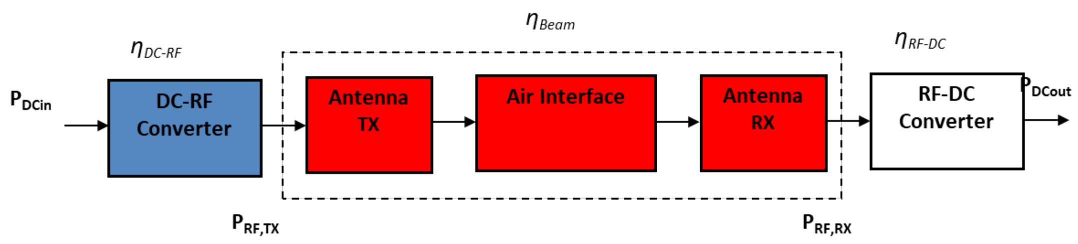


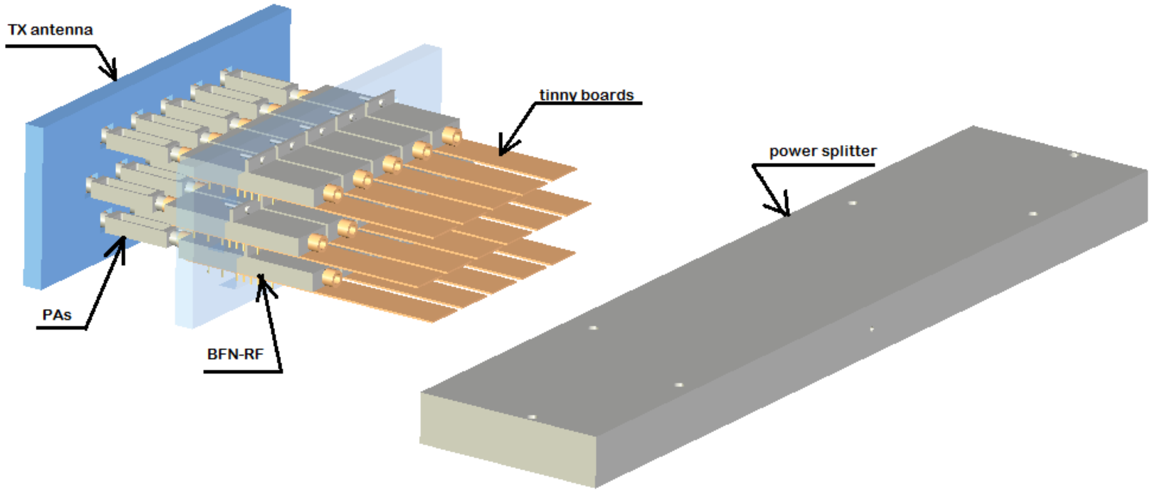


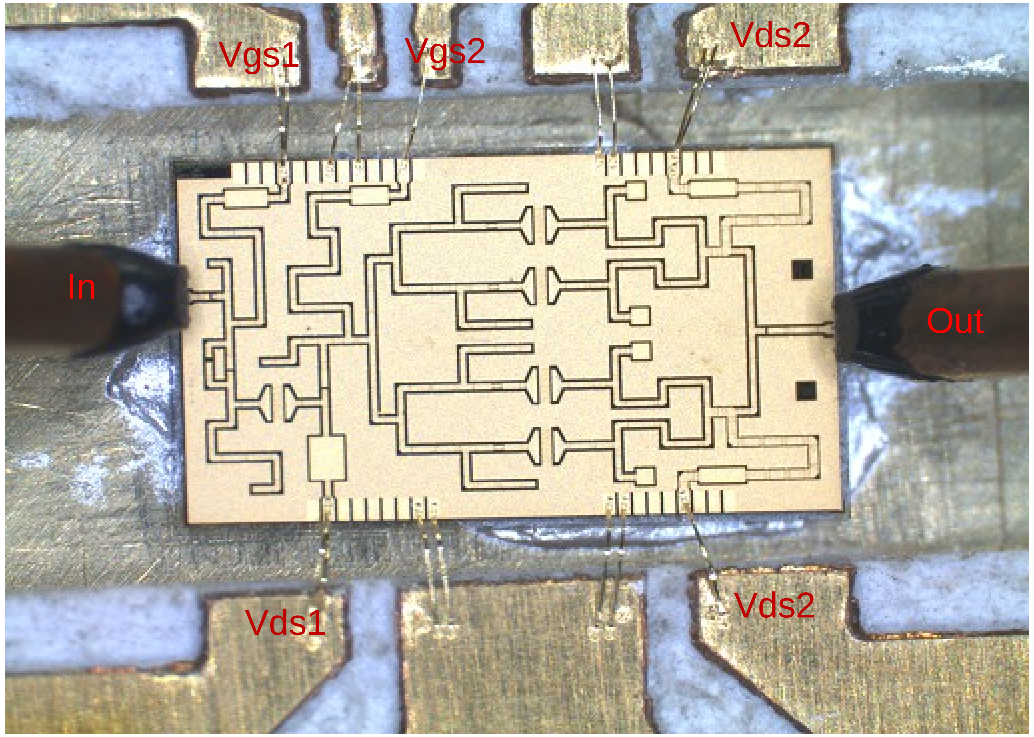
Possible Arrangements:

a. 6-7-2-**1**-3-4-5
b. 5-1-3-**4**-8-9-10
c. 14-15-16-**7**-2-1-6
d. 10-4-8-**9**-11-12-13

Active Antenna Arrays







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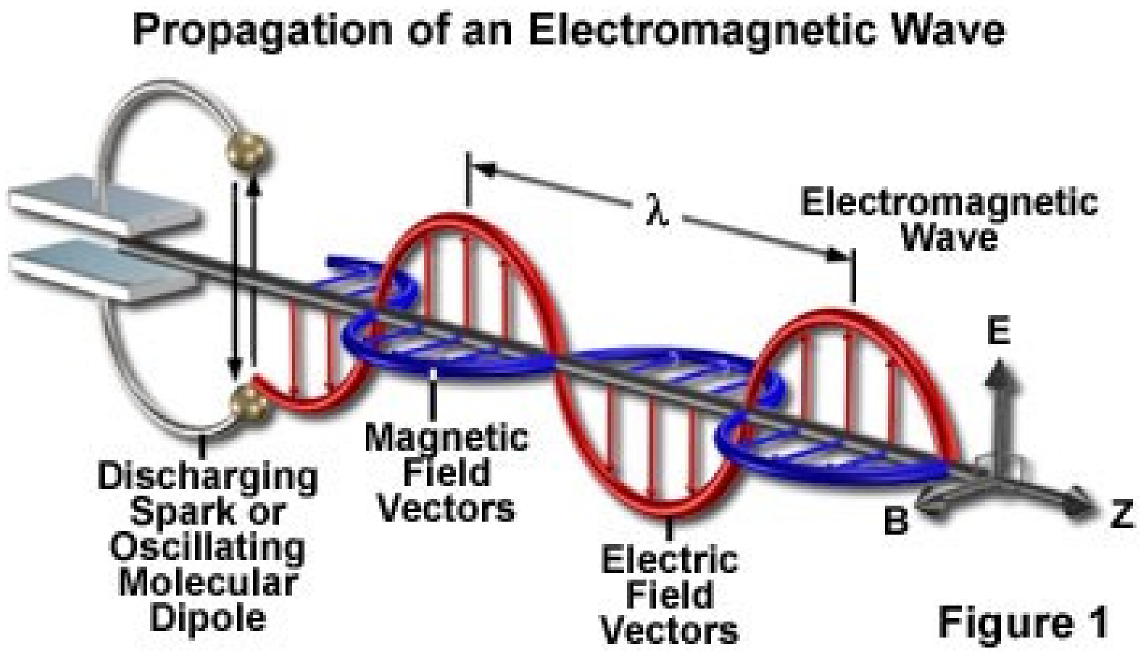
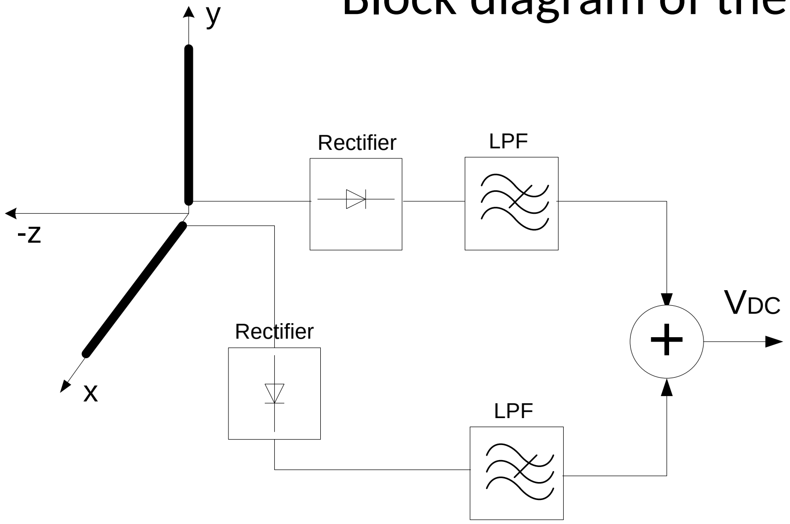
Electromagnetic Wave Propagation Basics

- EM wave is composed by an E-Field and a B-Field
- E and B are perpendicular to each other and perpendicular to the direction of propagation Z



Construction of the Dual-Polarized Antenna and Rectifier

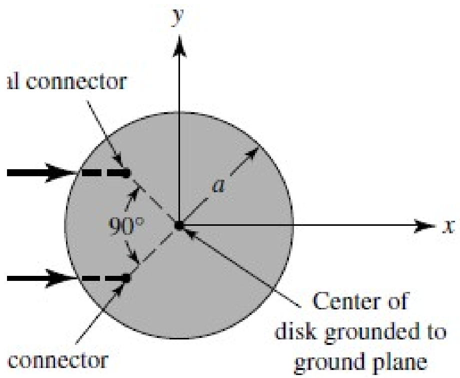
Block diagram of the Dual-polarized Rectenna (Antenna + Rectifier)



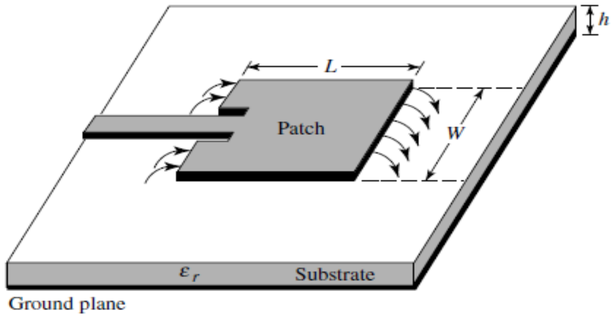
Circular shape has been chosen:

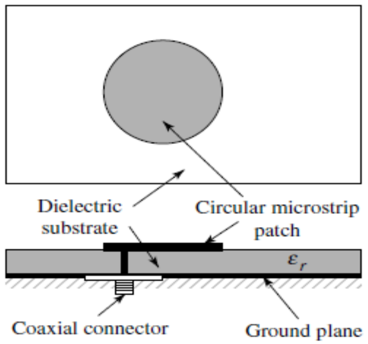
Easy fabrication

Good radiation characteristics



Microstrip Patch Antenna Topologies **[1]**



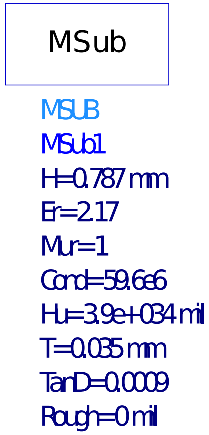


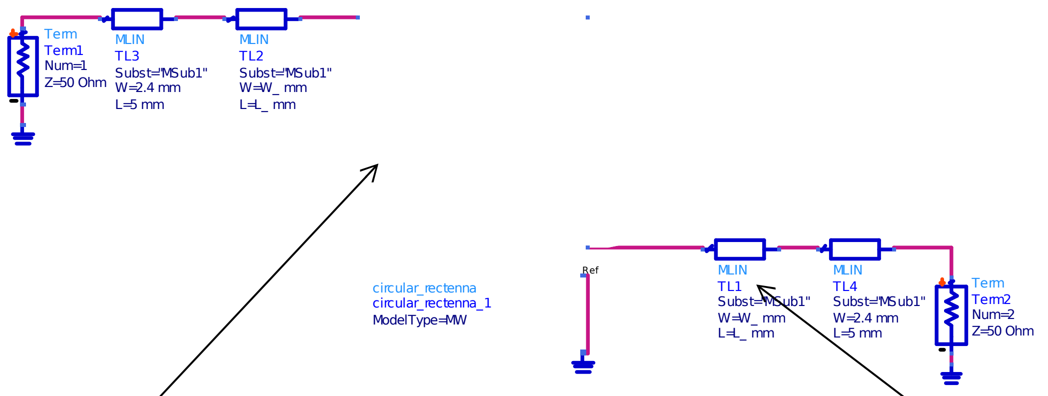
[1] *Antenna Theory: Analysis Design, Third Edition*, by Constantine A. Balanis

Antenna: Simulations and Measurements

ADS (Advanced Design Systems) EM-Circuit Co-Simulation

Substrate characteristics

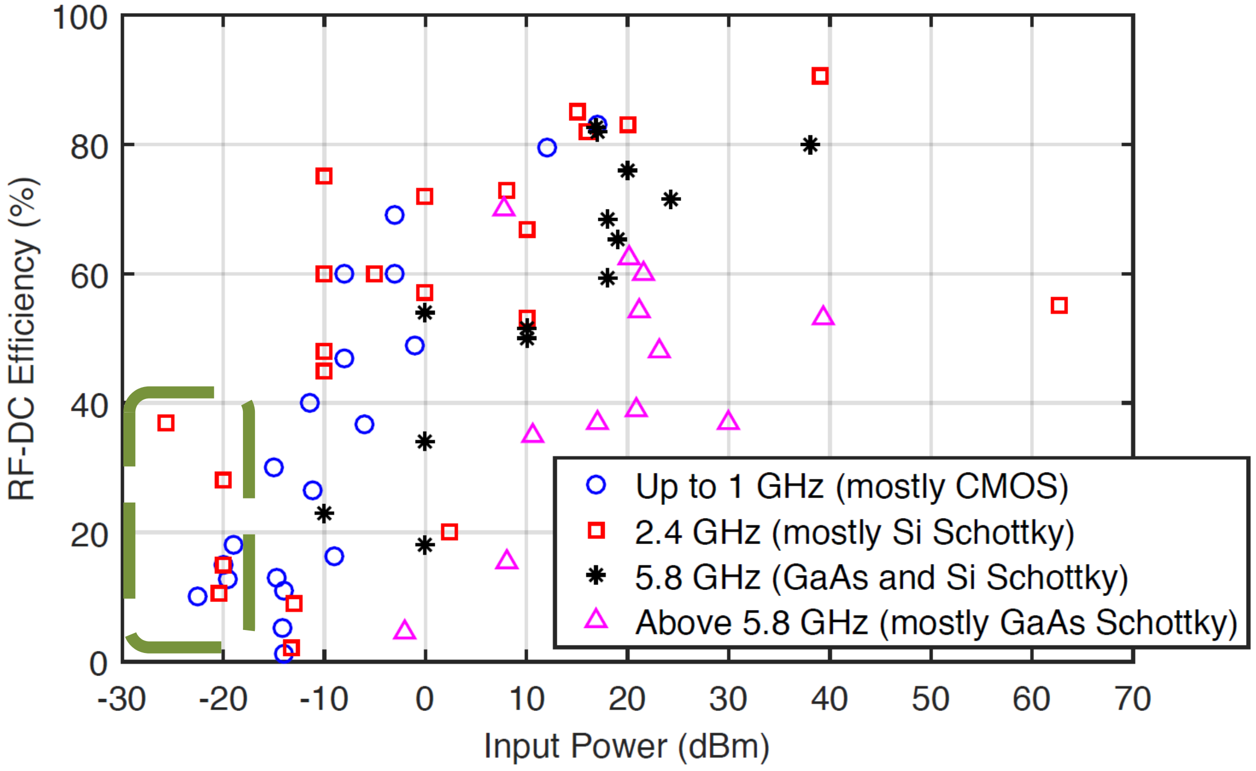




Circular patch antenna fed with two orthogonal paths

Matching circuit: quarter wavelength line

State-of-the art - RF-DC converters

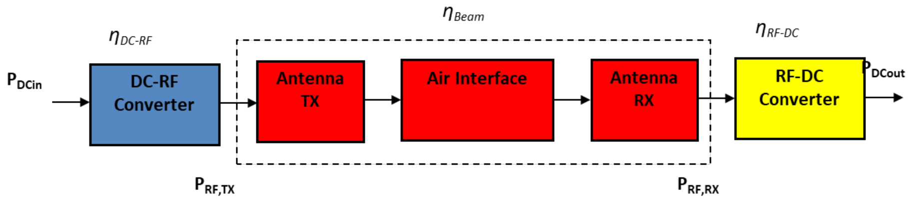


Less input power -> **less efficiency** (need to overcome the threshold barrier)
Increase frequency -> **less efficiency** (due to the increase of parasitic losses at higher frequencies)

Harvesting circuits for **UHF RFID** applications are mostly based on **CMOS technology** and operate at lower power levels (typically below 0 dBm).

Circuits for **SPS, MPT and WPT-oriented applications**, working at microwave range (2.4 GHz, 5.8 GHz and beyond), are based on discrete **Schottky diodes**, work at significantly higher input power levels and present increased efficiencies.

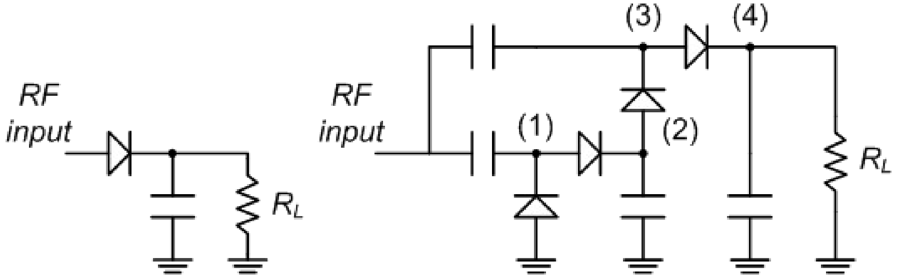
The efficiency of **ambient EM energy harvesting** at very low power levels (below -30 dBm) is reduced.



RF-DC Converters

- Rectifier circuits: envelope detector, charge pump circuits

  - Schottky diodes, low / zero barrier diodes

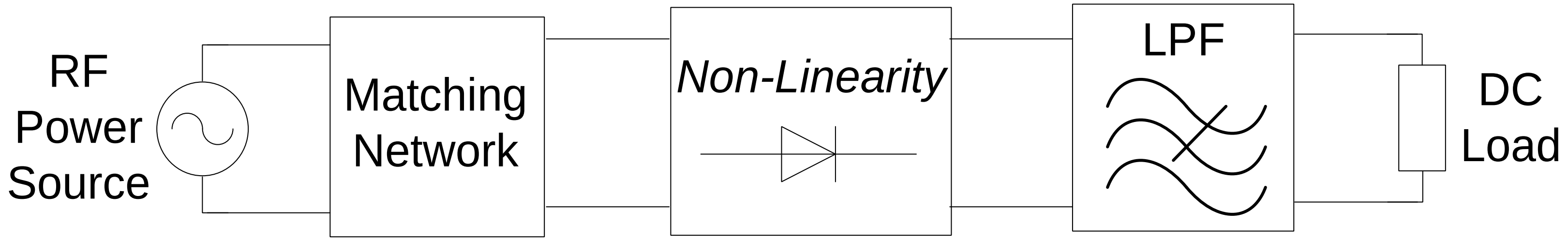


Reported efficiencies for available input power levels in the order of 10 uW are between 10% - 20%, and increase to 30%-60% for available power levels of 100uW.

RF-DC Conversion

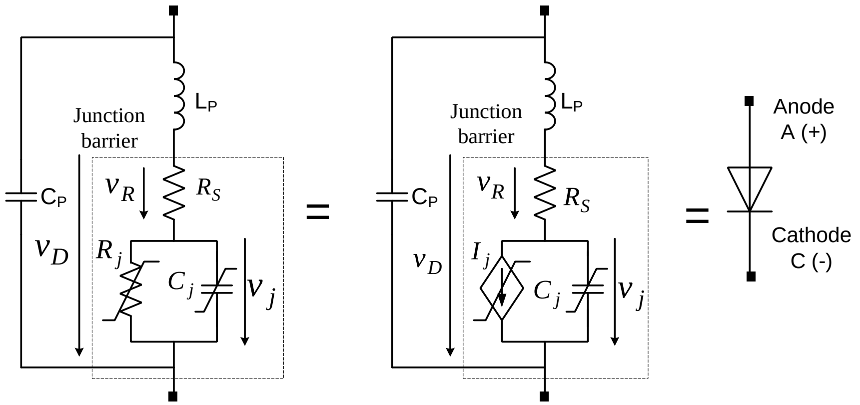
Desired component

$$y_{out} = NL[x_{in}(f_0)] = \boxed{Y(DC)} + Y(f_0) + Y(2f_0) + Y(3f_0) + _{\dots} + Y(nf_0)$$



RF-DC Conversion

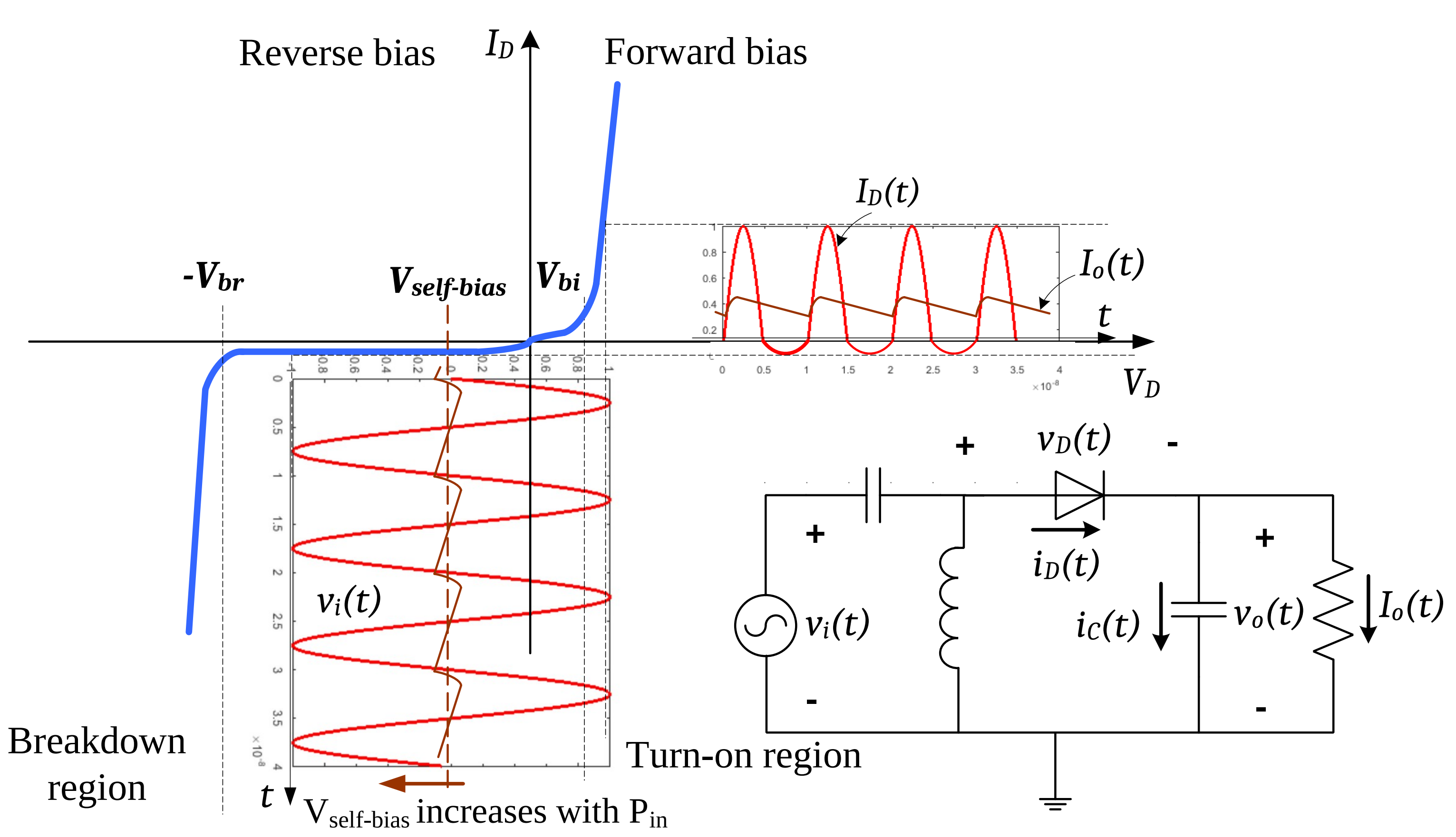
Schottky diode is one of most commonly used rectifying device



$$I_D = I_S(e^{\frac{qV_j}{\eta kT}} - 1) = I_S(e^{\frac{V_j}{\eta V_t}} - 1) = I_S(e^{\frac{V_D - R_S I_D}{\eta V_t}} - 1)$$

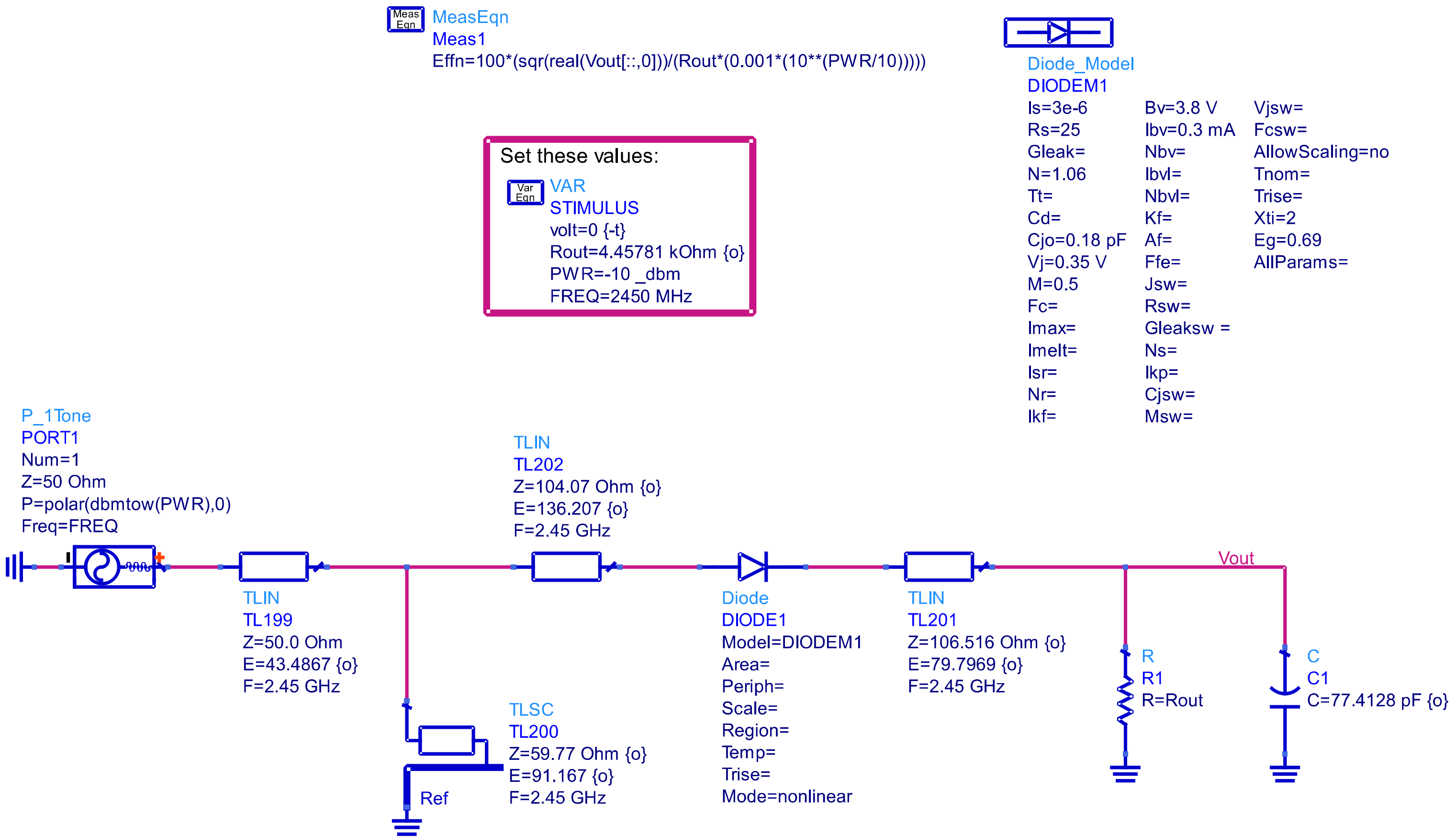
Gomes, H.; Testera, A.R.; Carvalho, N.B.; Fernandez-Barciela, M.; Remley, K.A., "Diode Power Probe Measurements of Wireless Signals," *Microwave Theory and Techniques, IEEE Transactions on* , vol.59, no.4, pp.987,997, April 2011

RF-DC Conversion



Rectifying devices exhibit a NON-ZERO turn-on voltage ✉ a certain amount of energy is needed to overcome the turn-on voltage ✉ low power level efficiency is degraded

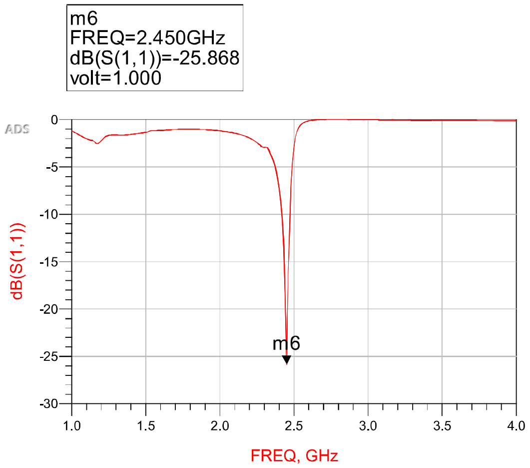
Design the RF-DC for 2.45 GHz

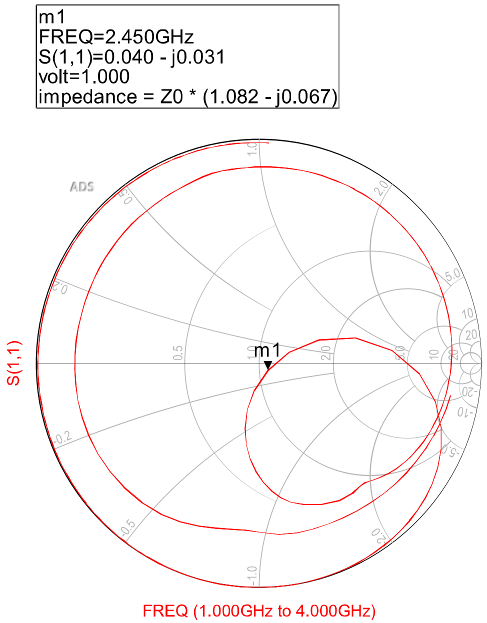


Results of RF-DC

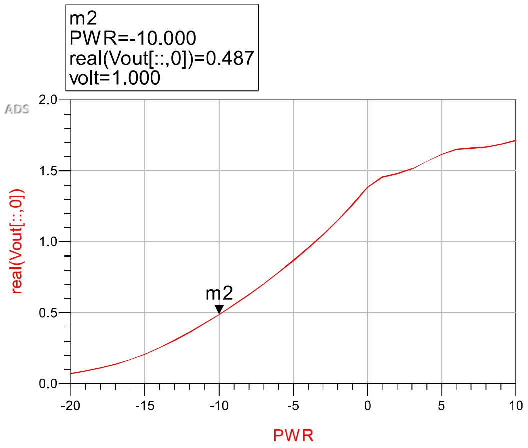
Using Large Signal S-parameters

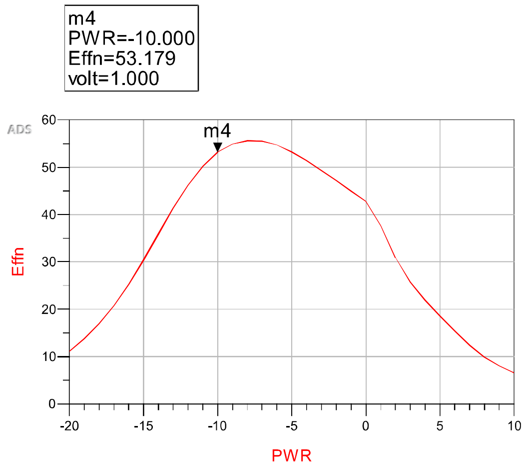
Matching Frequency = 2.45 GHz





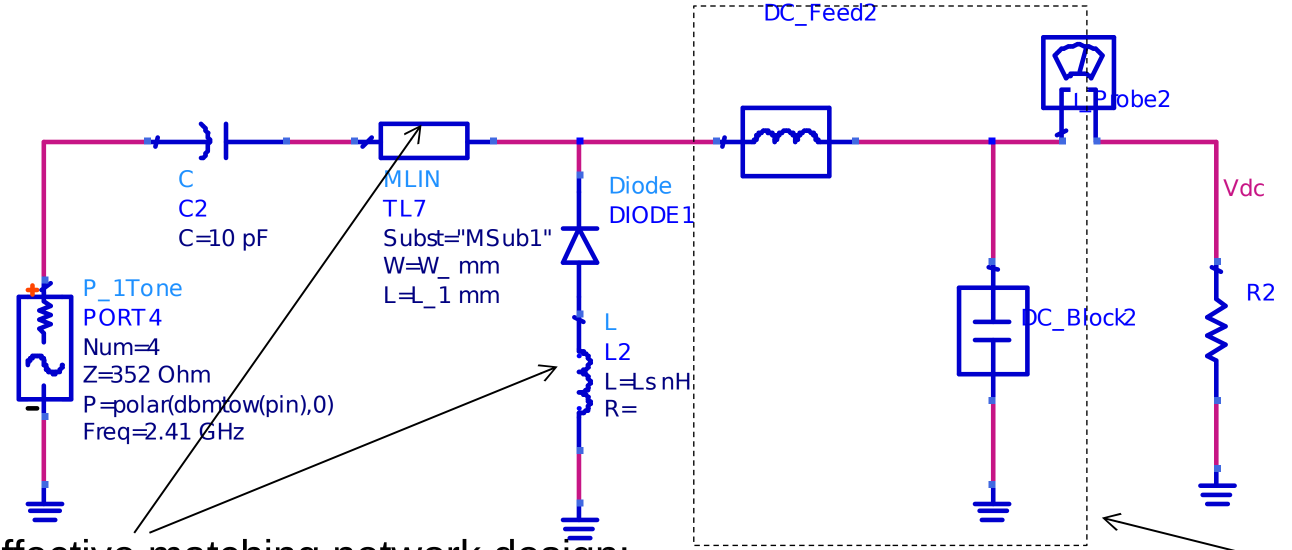
For -10 dBm (0.1 mW) of input power the output voltage generated is 0.487 V with 53.2 % of efficiency





Rectifier Design

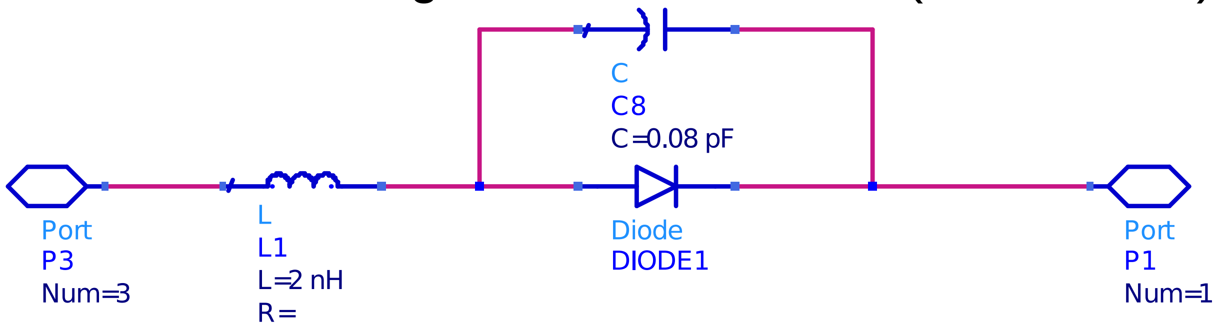
Single Diode rectifier, Low complexity matching network, Harmonic rejection



Simple and effective matching network design:
Series inductor + transmission line

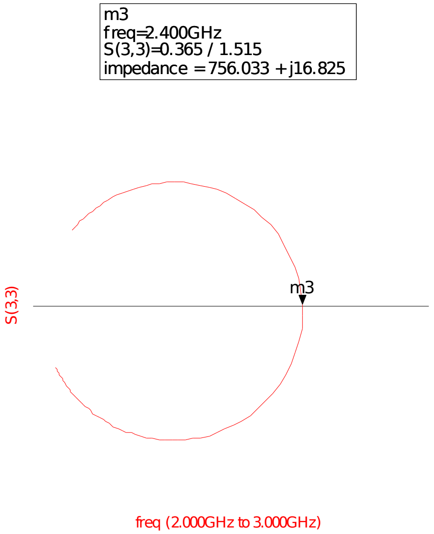
External Bias-Tee

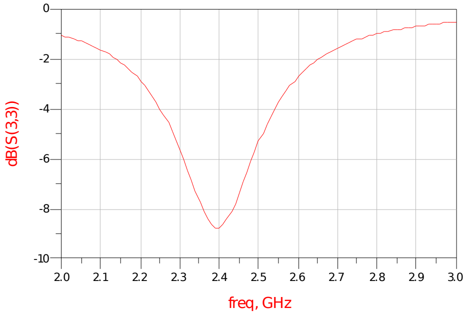
RF Diode Model including Parasitic elements (HSMS2850):



Rectifier Design: Simulations

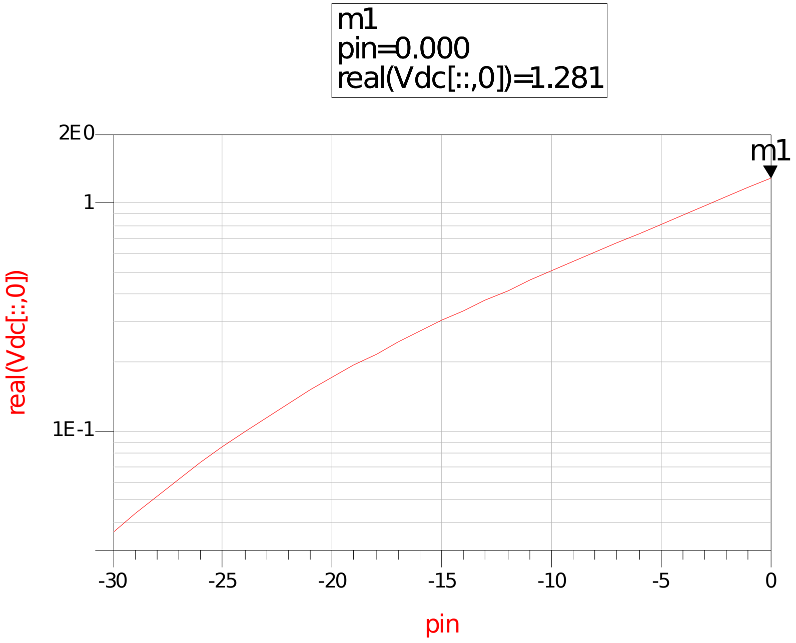
Return Loss of the rectifier circuit



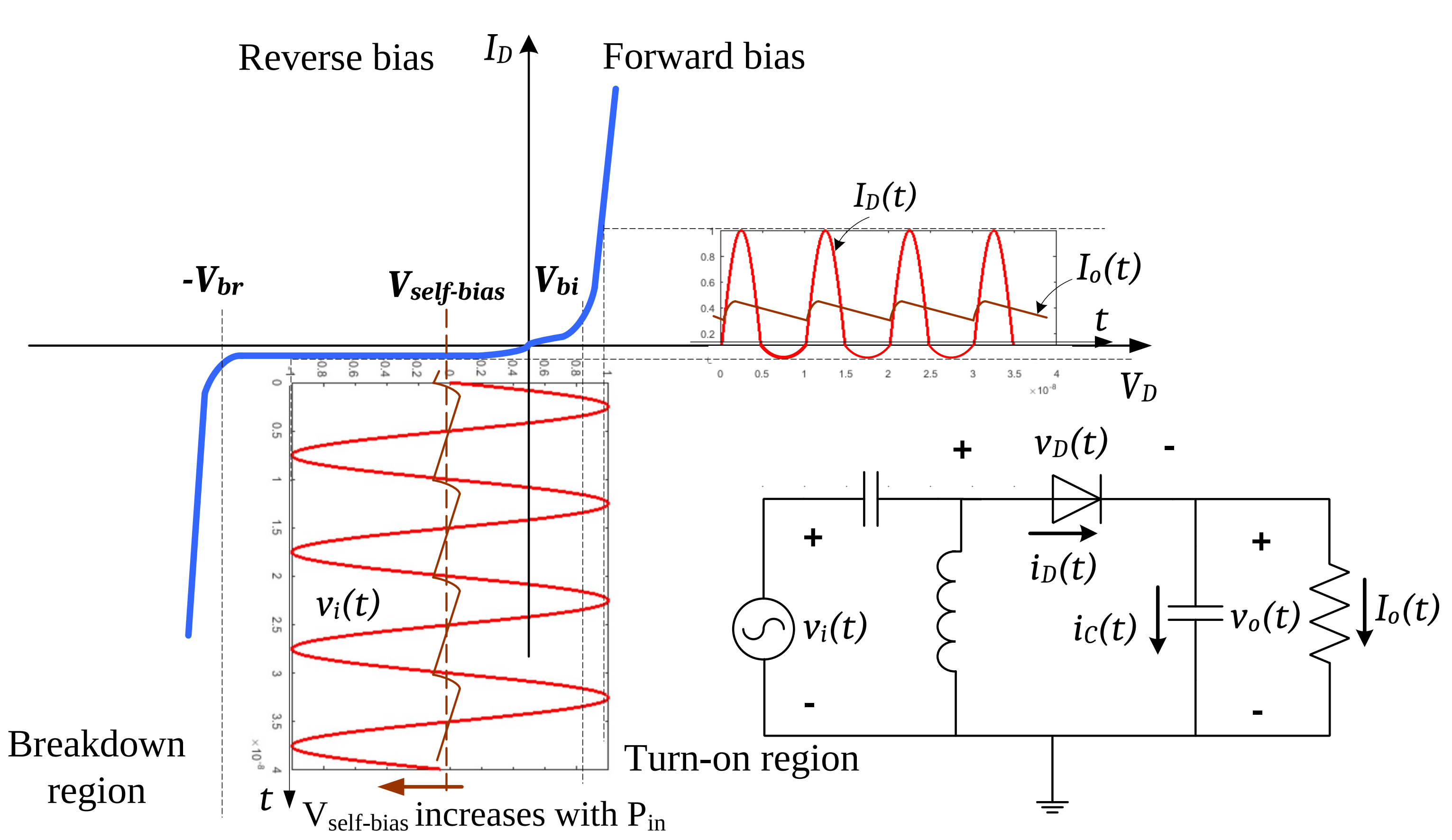


Rectification performance:

DC voltage as function of input power

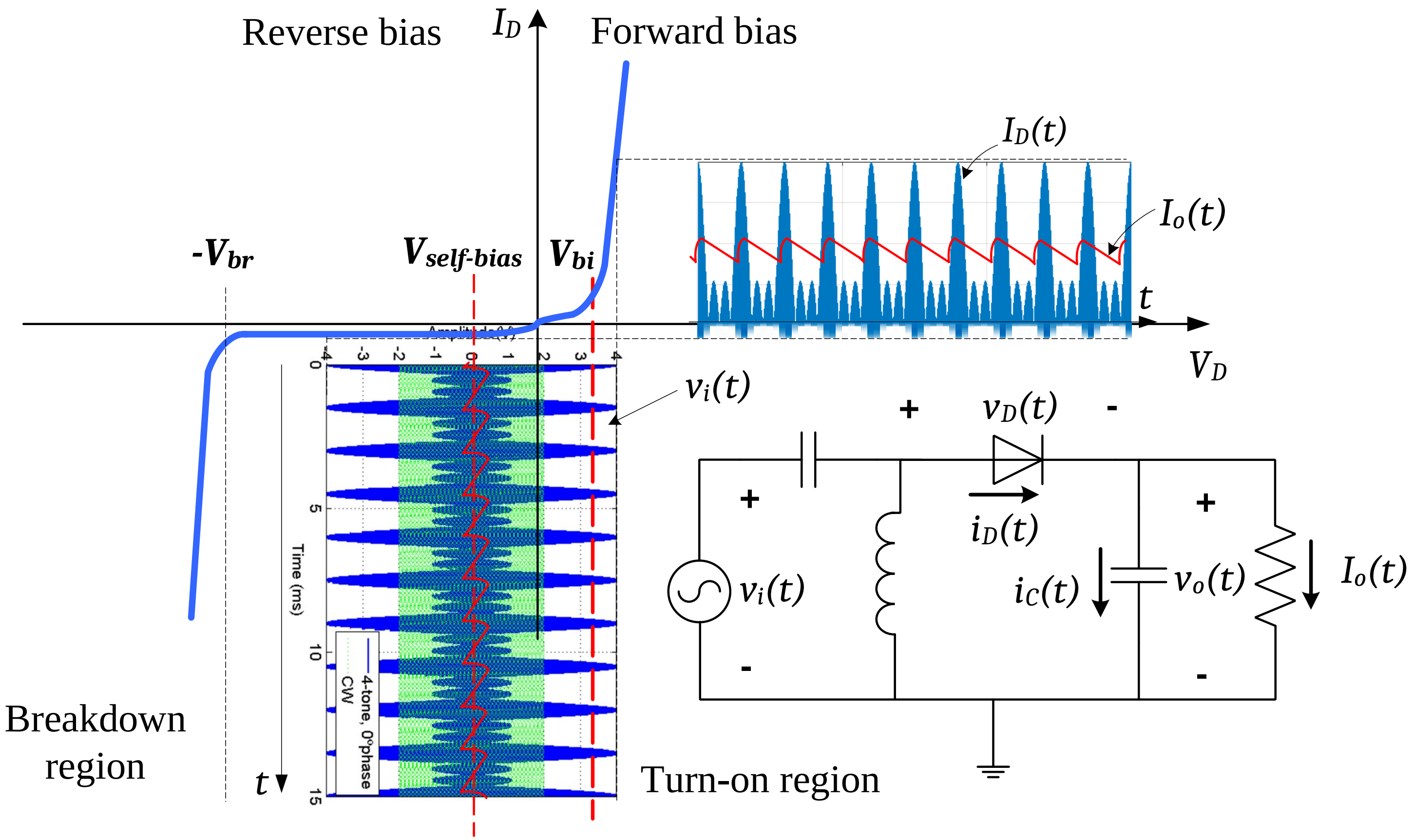


RF-DC Conversion



Rectifying devices exhibit a NON-ZERO turn-on voltage ✉ a certain amount of energy is needed to overcome the turn-on voltage ✉ low power level efficiency is degraded

Waveform design for improved RF-DC conversion efficiency



Rectifying devices exhibit a NON-ZERO turn-on voltage ✉ a certain amount of energy is needed to overcome the turn-on voltage ✉ low power level efficiency is degraded

Memory-less Taylor Model

The diode current can be approximated by a Taylor polynomial expansion

$$I_D = I_S(e^{\frac{qV_j}{\eta kT}} - 1) = I_S(e^{\frac{V_j}{\eta V_t}} - 1) \Rightarrow i_D(t) \approx \sum_{i=0}^{N} k_i\,(v_D(t) - V_{bias})^i$$

Since odd order terms do not contribute to DC, we take only the even order ones

$$i_D(t) \approx I_S(e^{\frac{V_{bias}}{\eta V_t}} - 1) + \frac{I_S}{2!}\frac{e^{\frac{V_{bias}}{nV_t}}}{(nV_t)^2}\left(v_i(t)\right)^2 + \frac{I_S}{4!}\frac{e^{\frac{V_{bias}}{nV_t}}}{(nV_t)^4}(v_i(t))^4 + \cdots$$

Waveform design for improved RF-DC conversion efficiency

- Considering a **CW** $v_i(t) = V_A cos(\omega_1 t + \varphi_1)$

DC component

RF second harmonic

$$i_{D\_CW}(t) \approx k_0 + \frac{1}{2}V_A^2 k_2 + \frac{3}{8}V_A^4 k_4 + \frac{1}{2}V_A^2 k_2 cos(2\omega_1 t + 2\varphi_1)$$

$$+ \frac{1}{2}V_A^4 k_4 \cos(2\omega_1 t + 2\varphi_1) + \frac{1}{8}V_A^4 k_4 \cos(4\omega_1 t + 4\varphi_1)$$

RF second harmonic

RF fourth harmonic

Multisine rectification

- Considering a **MS signal** with the same average power as the CW, $V_B=V_A/sqrt(N)$

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

The even-order contributes for the diode current the output come as follows:

Phase-independent component

$$I_{DC}(\varphi_1, \varphi_2, \varphi_3, \varphi_4) \approx k_0 + 0.5V_A^2 k_2 + 0.65625 V_A^4 k_4$$

Phase-dependent component

$$+ 0.09375 V_A^4 k_4 \cos(2\varphi_3 - \varphi_2 - \varphi_4)$$
$$+ 0.09375 V_A^4 k_4 \cos(-2\varphi_2 + \varphi_1 + \varphi_3)$$
$$+ 0.1875 V_A^4 k_4 \cos(\varphi_1 - \varphi_2 - \varphi_3 + \varphi_4)$$

Waveform design for improved RF-DC conversion efficiency

The optimization problem: Maximize the phase-dependent component

$$\begin{cases} \cos(Arg1) = 0 \\ \cos(Arg2) = 0 \\ \cos(Arg3) = 0 \end{cases} \qquad \begin{cases} Arg1 = 2\varphi_3 - \varphi_2 - \varphi_4 \\ Arg2 = -2\varphi_2 + \varphi_1 + \varphi_3 \\ Arg3 = \varphi_1 - \varphi_2 - \varphi_3 + \varphi_4 \end{cases}$$

- The trivial solution:

$$\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0^{o}.$$

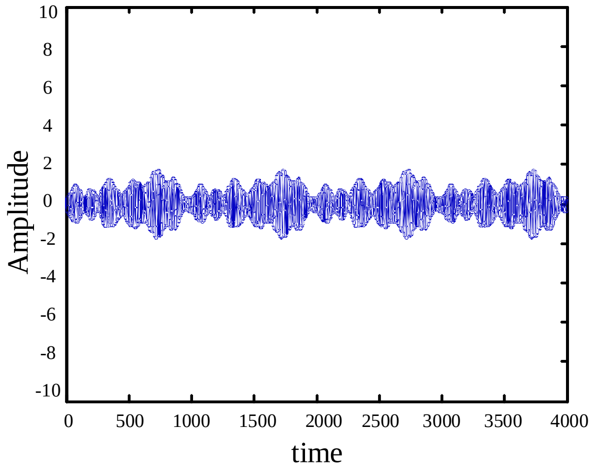
- The general solution consists of using a phase-reference and a constant phase progression among carriers:

$$(\varphi_2 = \varphi_1 + \Delta\varphi;\ \varphi_3 = \varphi_1 + 2\Delta\varphi;\ \varphi_4 = \varphi_1 + 3\Delta\varphi)$$

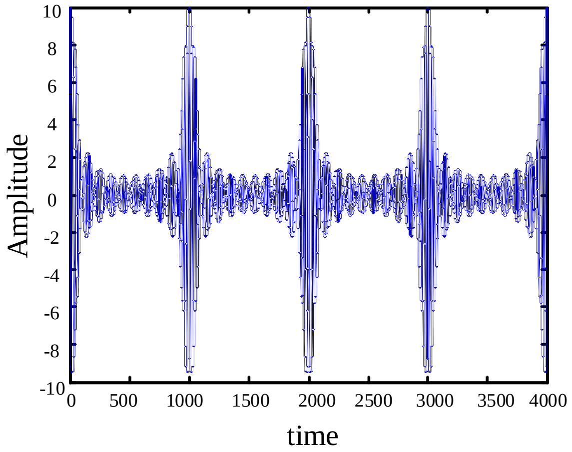
$$\begin{cases} Arg1 = 2(\varphi_1 + 2\Delta\varphi) - (\varphi_1 + \Delta\varphi) - (\varphi_1 + 3\Delta\varphi) = 0 \\ Arg2 = -2(\varphi_1 + \Delta\varphi) + \varphi_1 + (\varphi_1 + 2\Delta\varphi) = 0 \\ Arg3 = \varphi_1 - (\varphi_1 + \Delta\varphi) - (\varphi_1 + 2\Delta\varphi) + (\varphi_1 + 3\Delta\varphi) = 0 \end{cases}$$

Waveform design for improved RF-DC conversion efficiency

10 tones with Random phases ✉
Low PAPR

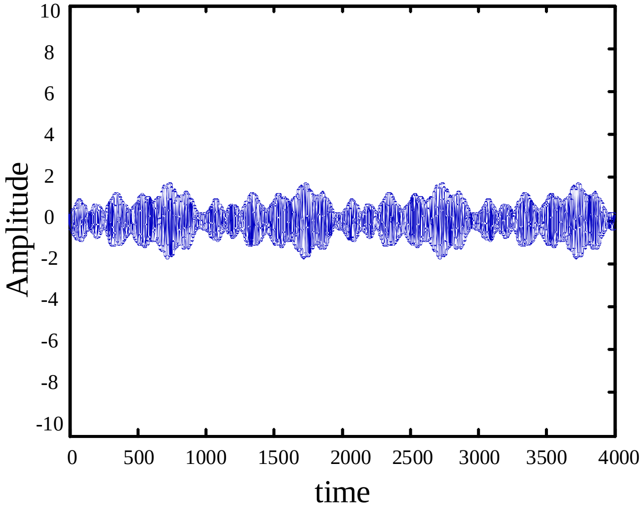


10 tones with **Synced phases** ✉
Max PAPR

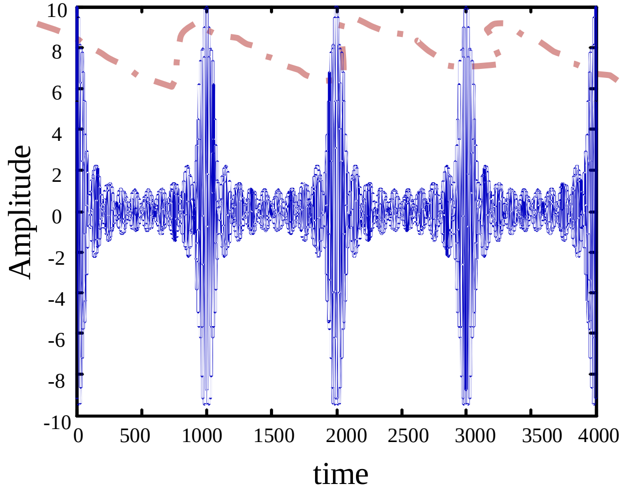


Waveform design for improved RF-DC conversion efficiency

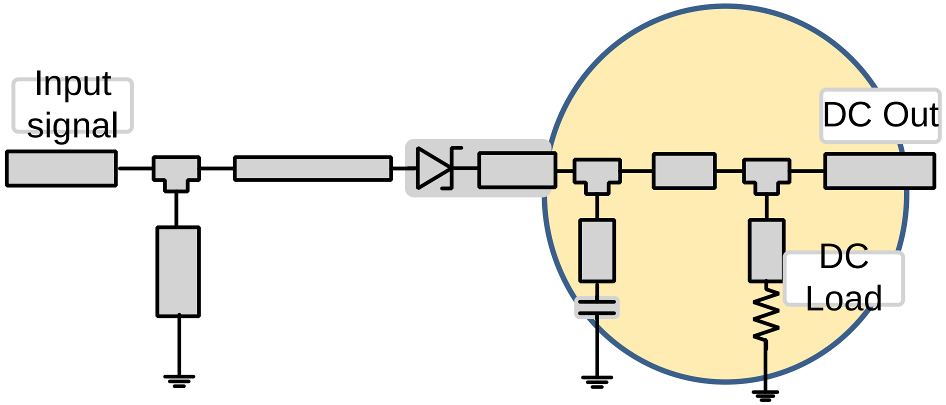
Boaventura, A.; Collado, A.; Carvalho, N.B.; Georgiadis, A., "Optimum behavior: Wireless power transmission system design through behavioral models and efficient synthesis techniques," *Microwave Magazine, IEEE* , vol.14, no.2, pp.26,35, March-April 2013

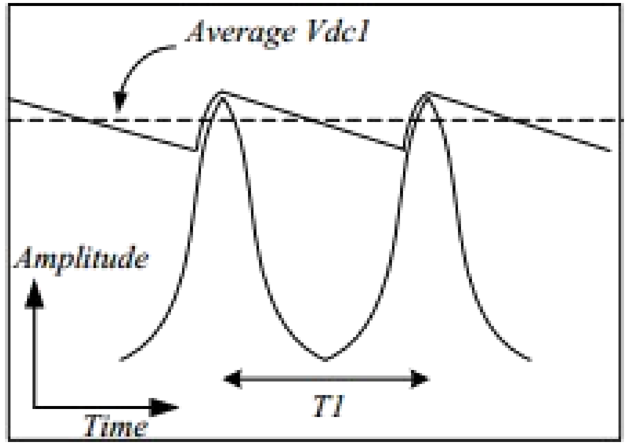


10 Tones of Randomized Phase

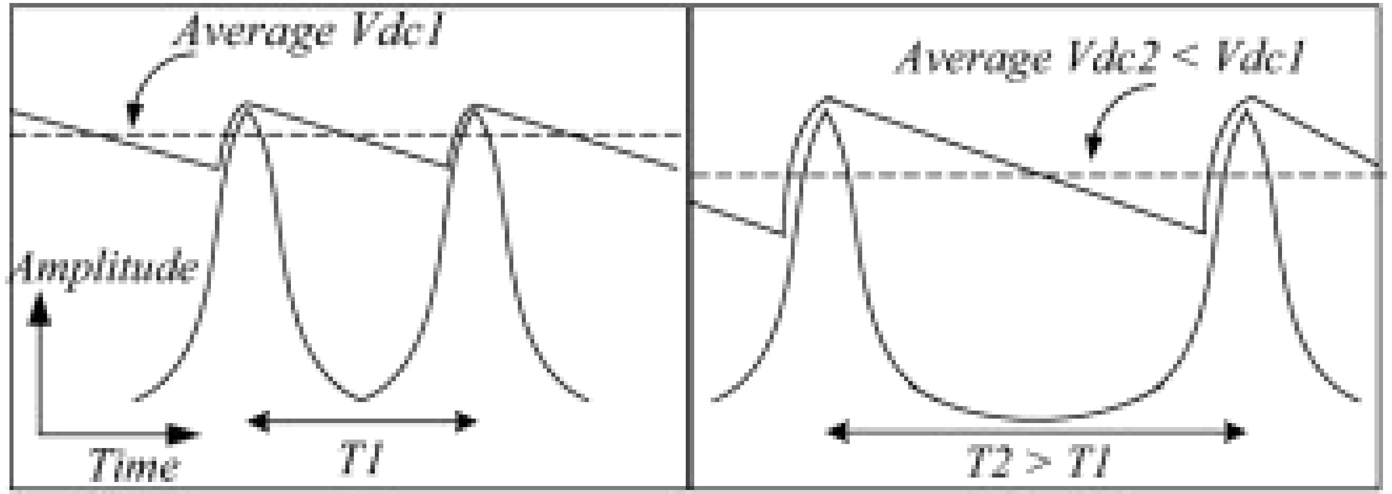


10 Tones of Equal Phase





Waveform design for improved RF-DC conversion efficiency



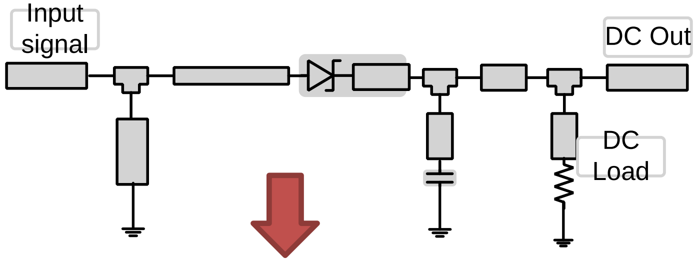
Tone separation is an important aspect to account for

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

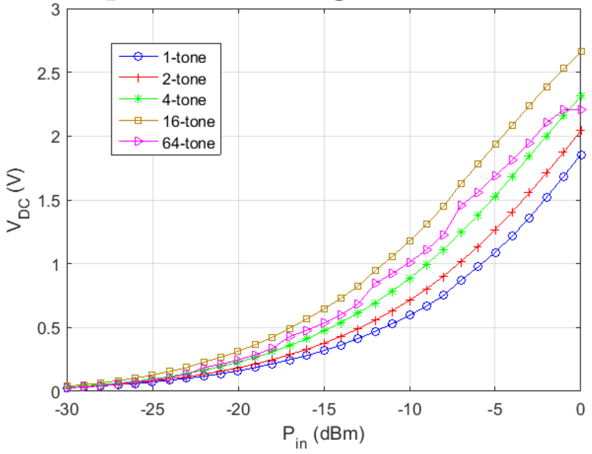
Waveform design for improved RF-DC conversion efficiency

Circuits tested under CW and several MS signals with the same average power

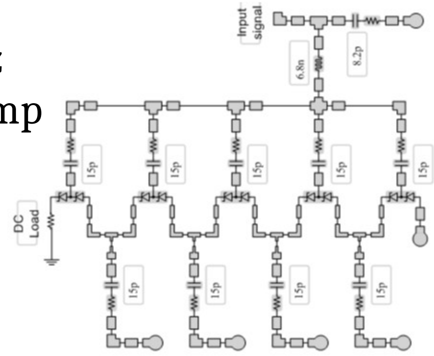
2.4 GHz detector



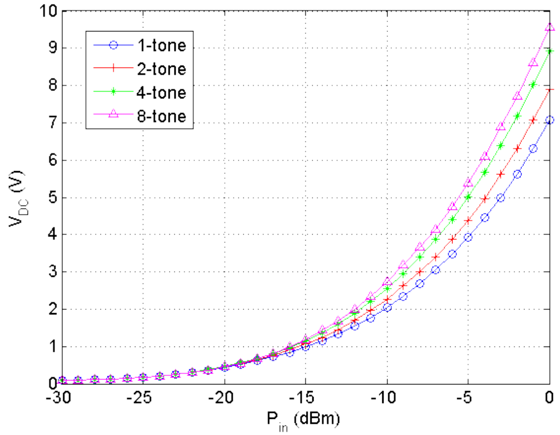
Output DC Voltage as a function of Pin



866 MHz
Charge pump



Output DC Voltage as a function of Pin



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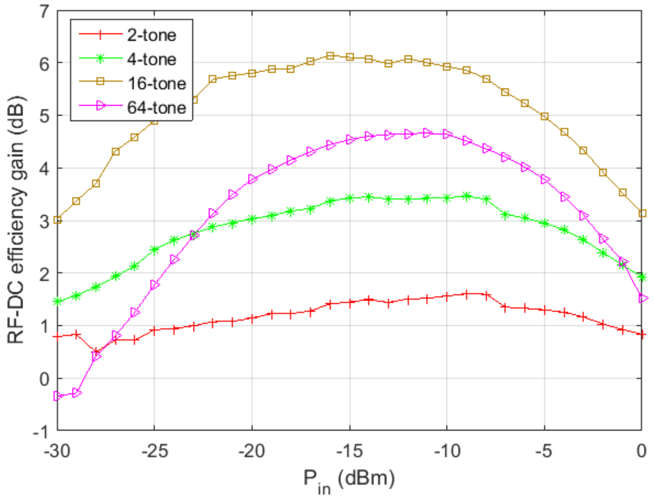
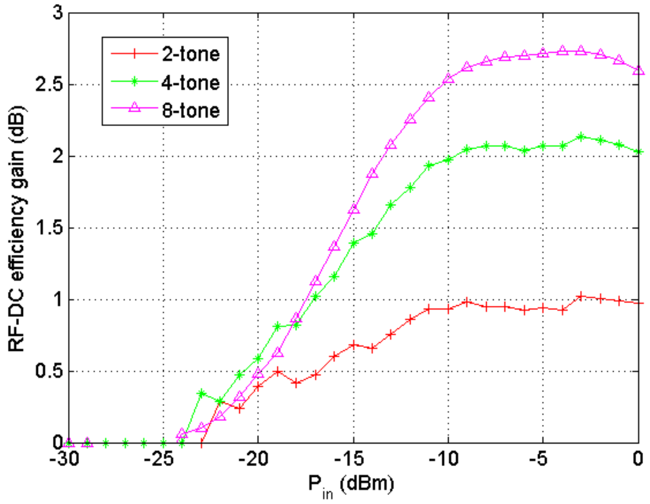
Waveform design for improved RF-DC conversion efficiency

Efficiency gain as a function of Pin



Efficiency gain as a function of Pin



❖ MS signals can improve the performance of RF-DC converter circuits.

❖ This answers affirmatively to the first question of this thesis!

❖ These results suggest that this approach can enhance backscatter systems.

Boaventura, A.S.; Carvalho, N.B., "Maximizing DC power in energy harvesting circuits using multisine excitation," *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International* , vol., no., pp.1,4, 5-10 June 2011

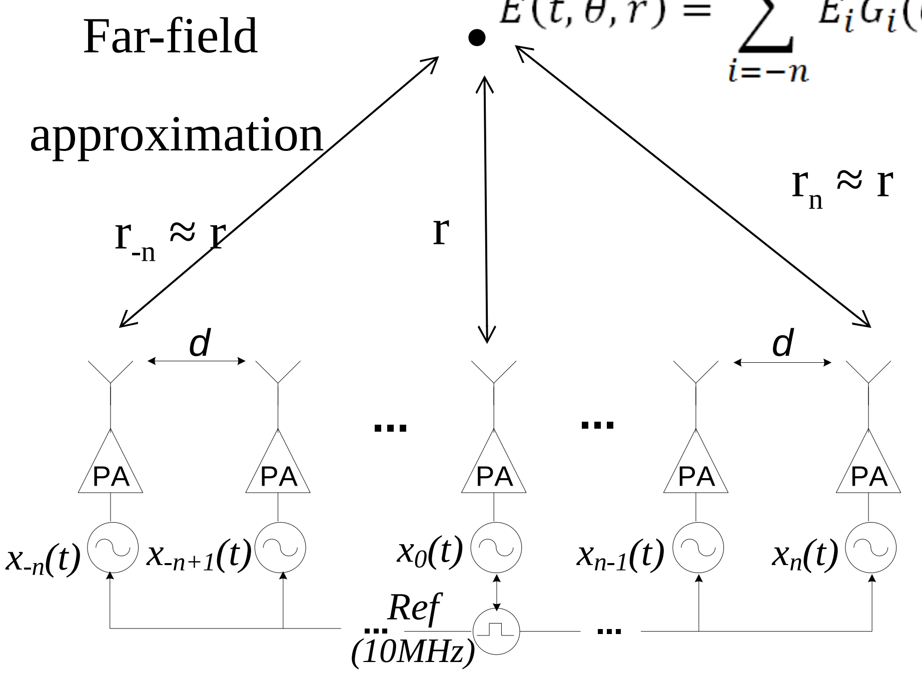
Space power combining of high PAPR Multisine signals

- High PAPR Signal amplification is challenging, since Non-linear Distortion, Spectrum Regrowth and **Signal Clipping** can occur

The proposed approach

$$E(t,\theta,r) = \sum_{i=-n}^{n} E_i G_i(\theta) e^{j[\omega_i t + kr + \phi_i]}$$

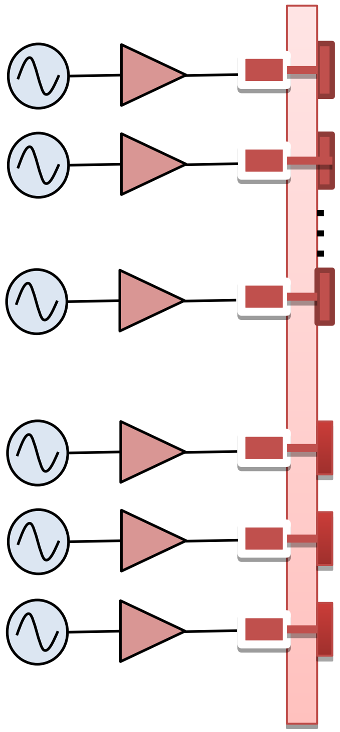
- ✓ Passive free-space power combining
- ✓ PA's operate at CW regime



Soares Boaventura, A.J.; Collado, A.; Georgiadis, A.; Borges Carvalho, N., "Spatial Power Combining of Multi-Sine Signals for Wireless Power Transmission Applications," *Microwave Theory and Techniques, IEEE Transactions on* , vol.PP, no.99, pp.1,10

Space power combining of high PAPR Multisine signals

- Synchronization of the MS sub-carriers is essential to achieve high PAPR

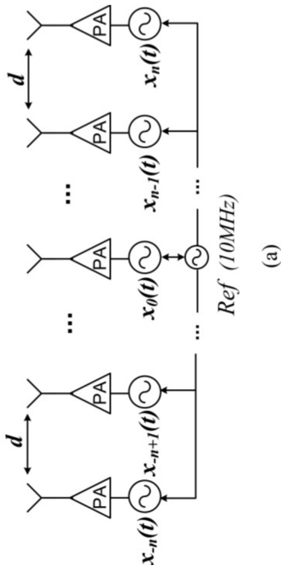


Two synchronization schemes are proposed

External synchronization
using a 10 MHz Ref. oscillator

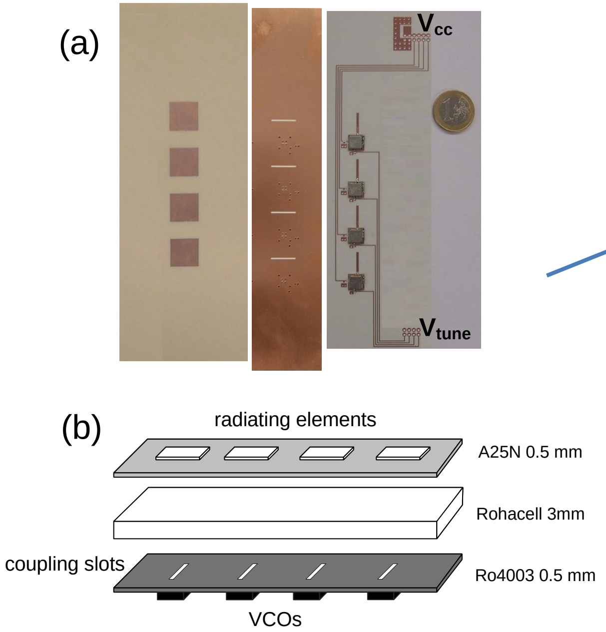
Mode-locking synchronization for maximum PAPR:
Equally-spaced freq.
&
Const. phase progression

$$\begin{cases} \omega_i = \omega_0 + i\Delta\omega \\ \varphi_{i+1} - \varphi_i = \Delta\varphi \end{cases}$$



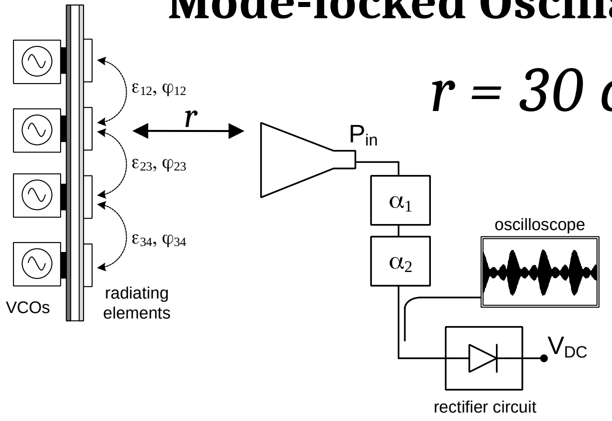
Space power combining of high PAPR Multisine signals

Measurements

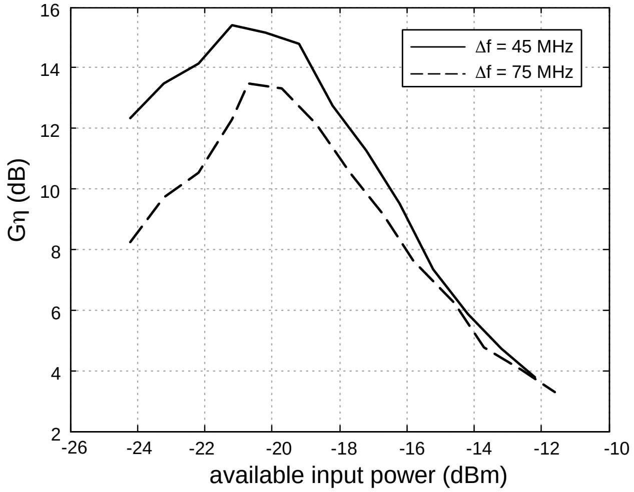


Mode-locked Oscillator Arrays

$r = 30\ cm$



Efficiency Gain as function of Pin



A maximum gain of up to 15 dB obtained was obtained for a detector @ 6GHz under 4-tone MS

A Selective, Tracking and Power Adaptive WPT system

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radio systems

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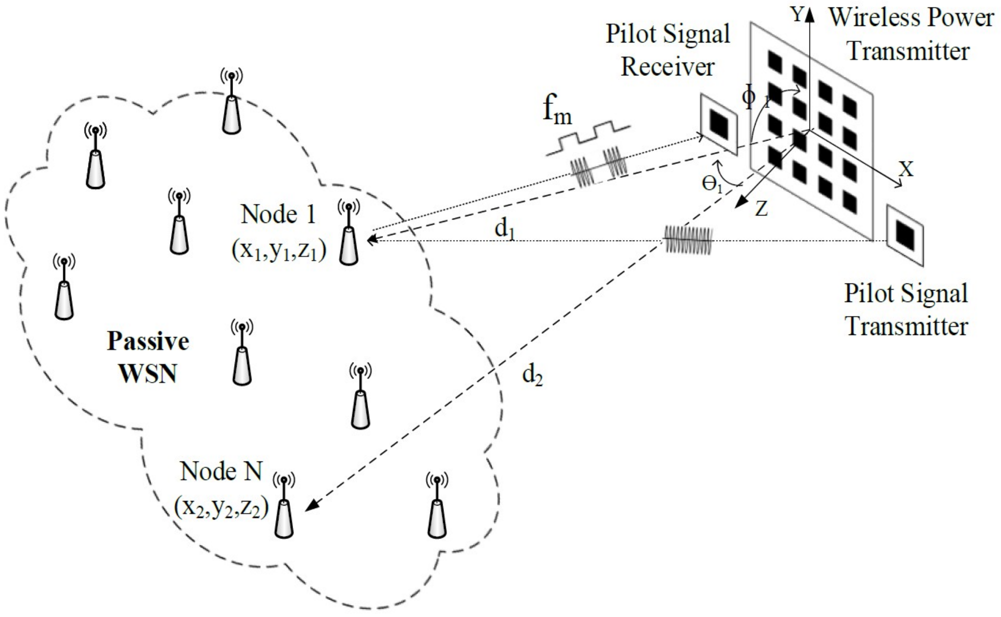
Selective, Tracking and Power Adaptive WPT System

Consider the following scenario:

- Prior to the transmitter installation, several **battery-less** devices were deployed.
- Assume that each device is a simple **actuator** or a **low-power** sensor which only generates digital data.



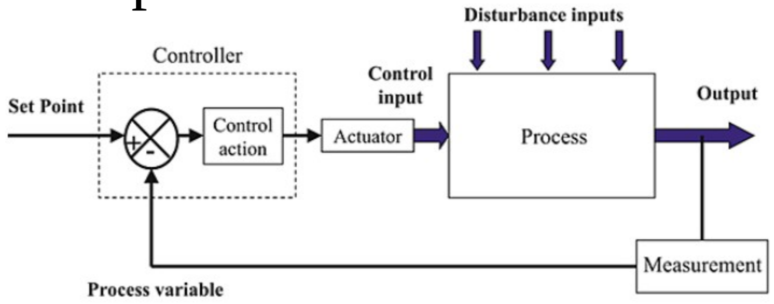
- Each device will require different transmitted energy, depending on their position and/or blockage, fading or shadowing

Selective, Tracking and Power Adaptive WPT System

- If the target is an **Actuator**:

  How to wirelessly **locate** and **charge** a device without a radio?

Full wireless? Even power?



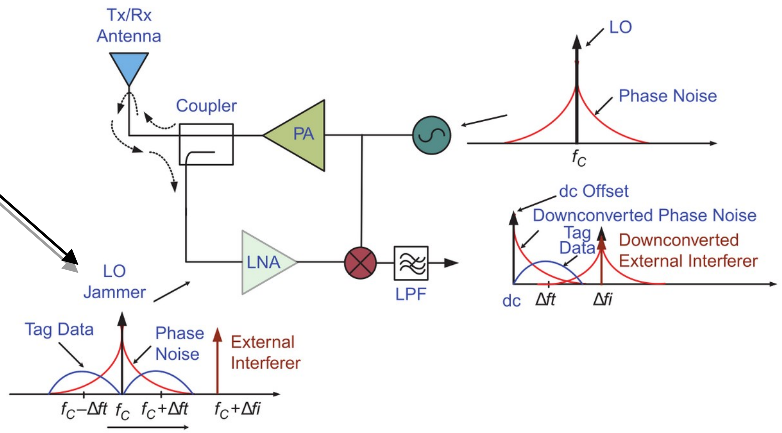
- Even if it has…

  Wireless power shall be transmitted on a different channel/frequency

  Avoid Self-Jamming…

- How to obtain information about the WPT channel?

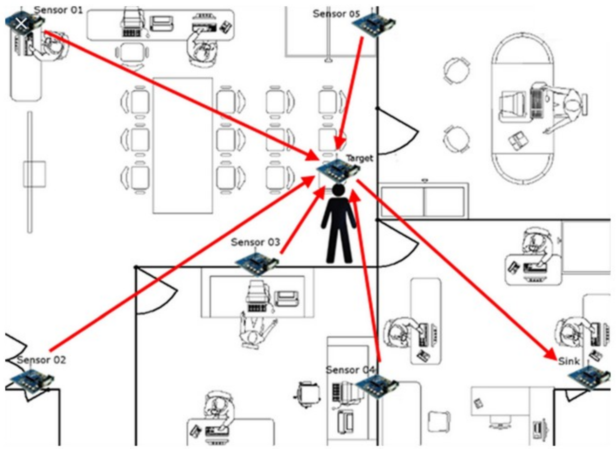
Very strong LO/ WPT carrier



Selective, Tracking and Power Adaptive WPT System

Can not initiate any Comm.

It must be energized first!!



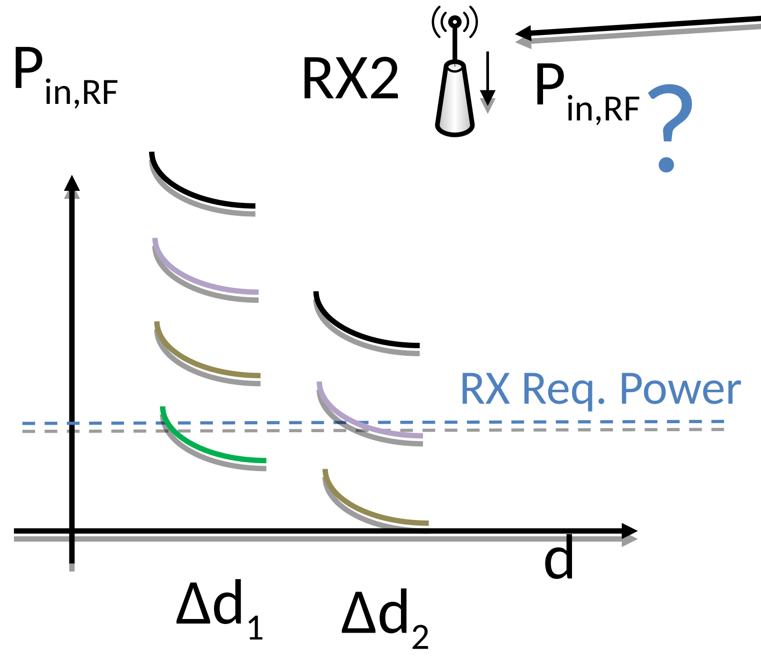
Basic Wireless localization techniques such as:

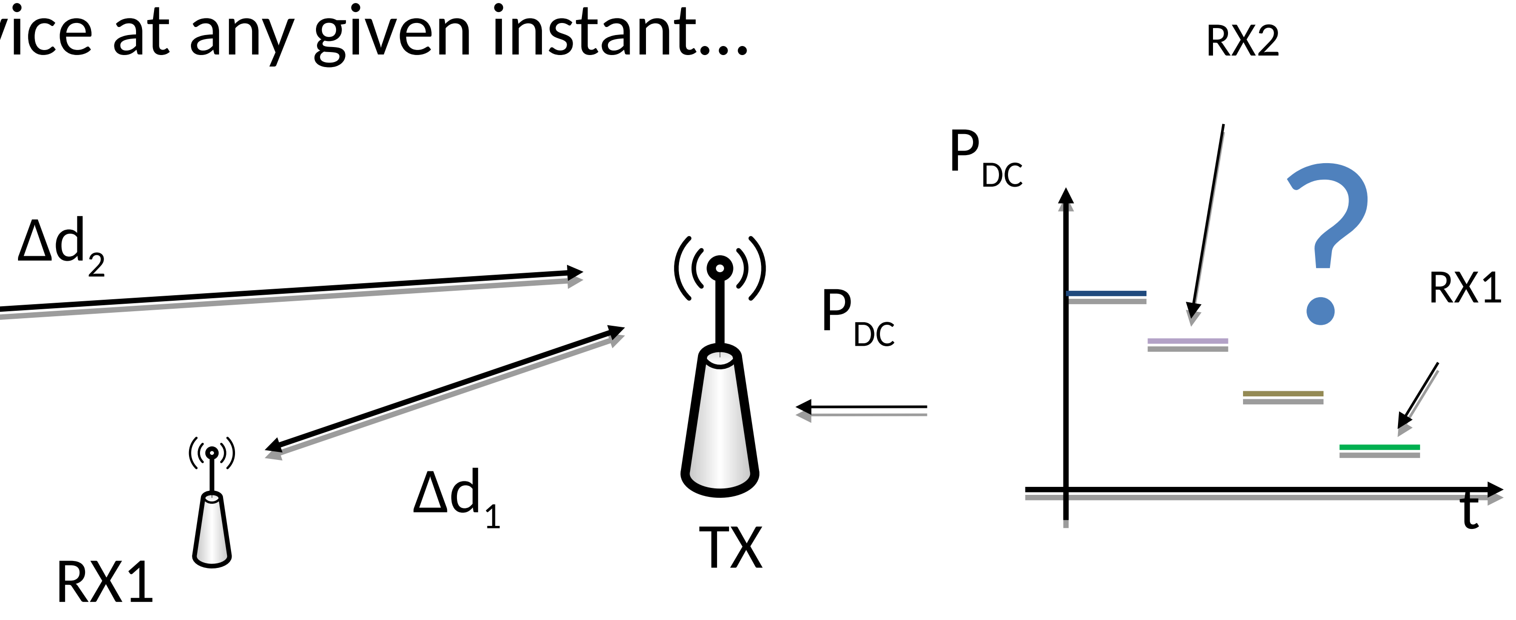
- Received Signal Strength
- Angle-of-Arrival
- Time-of-Arrival

NOT applicable!

Selective, Tracking and Power Adaptive WPT System

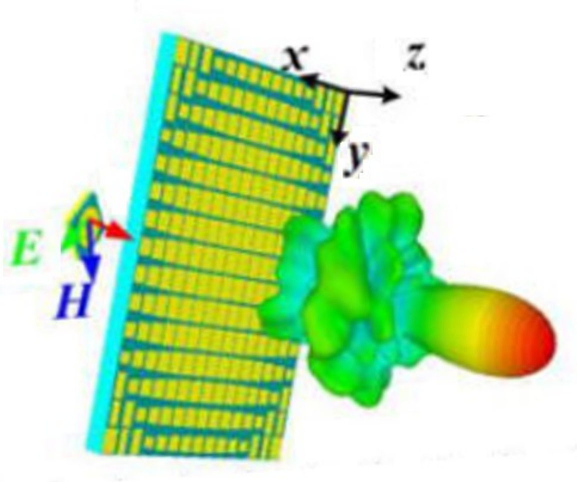
- And... What if we want to know how much power is available for the device at any given instant...

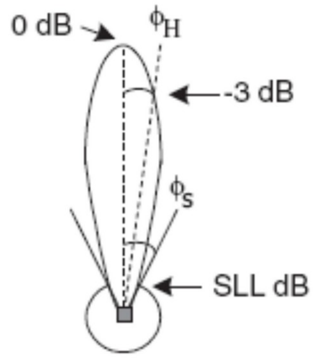




... so as to **Power Adapt** and use the minimum required DC power at the transmitter?

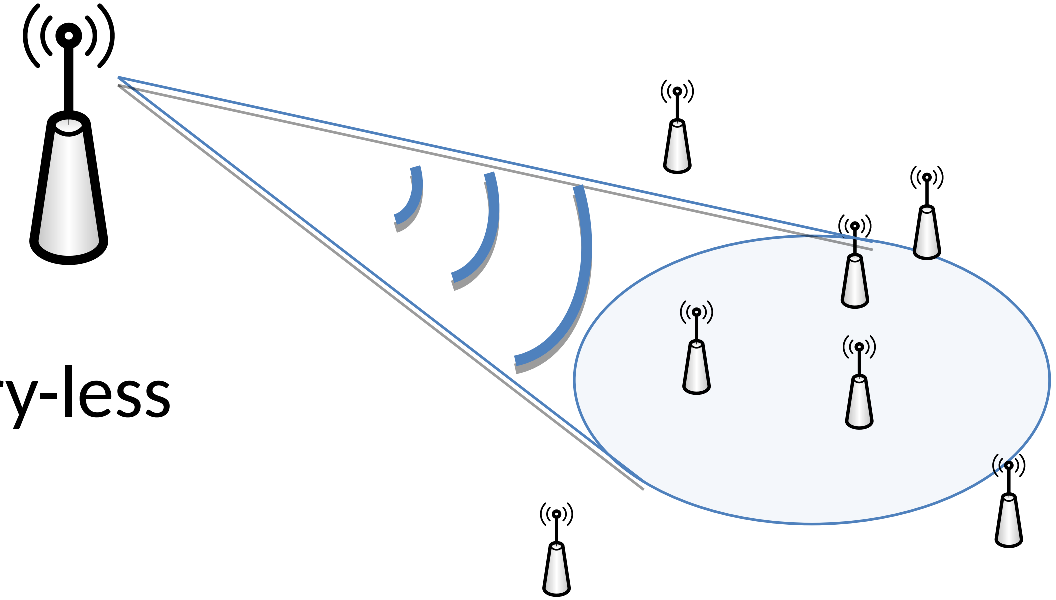
Selective, Tracking and Power Adaptive WPT System





- If several devices are placed within the main beamwidth – All of them may turn on!

- Some sort of **Selectivity** is required



- Not so simple to realize with battery-less devices….

Selective, Tracking and Power Adaptive WPT System

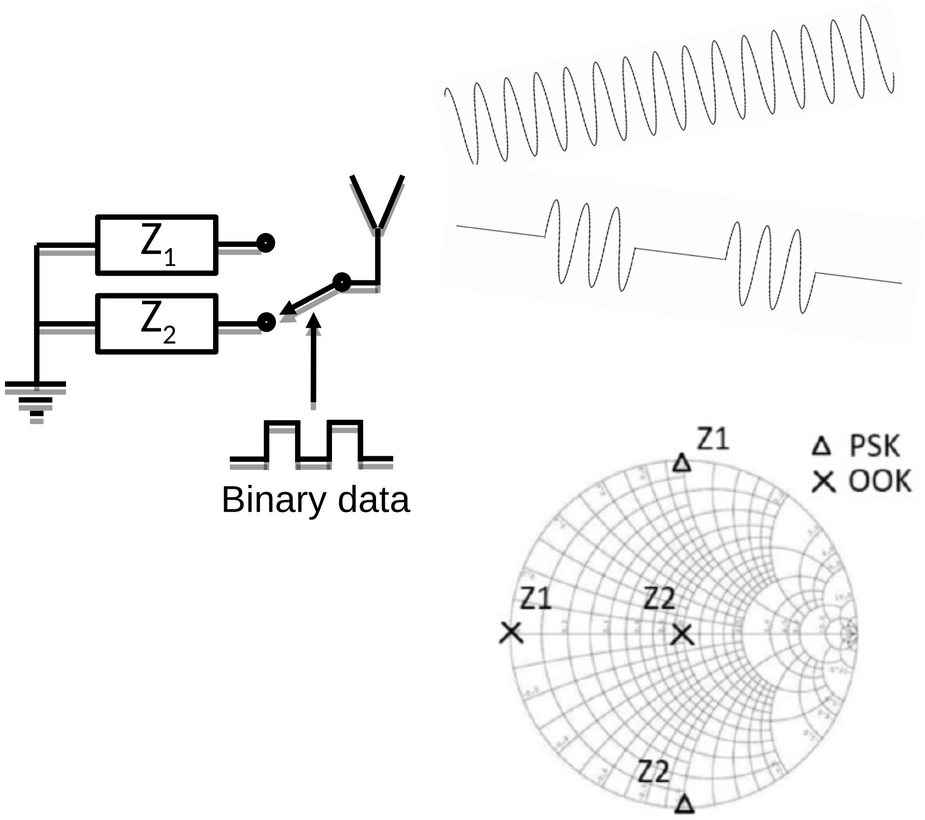
Design a complete far-field WPT system with the following features:

- May be easily integrated with current actuator/sensors;
- Must provide accurate energy transmission, tracking and power adaptive in order to attain high transfer efficiency;
- Must be able to select the desired target;
- Shall handle battery-less devices and be independent of the actuator/sensor to be powered.

Selective, Tracking and Power Adaptive WPT System

- To achieve the desired goals, there must be some kind of **feedback** provided by the receiver.

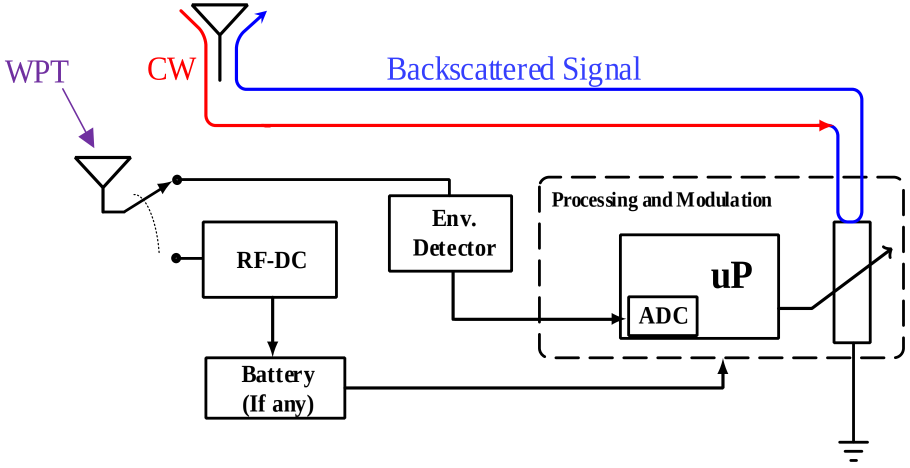
- **Backscatter Communications**
  - Low complexity
  - Very low power consumption
  - Low cost

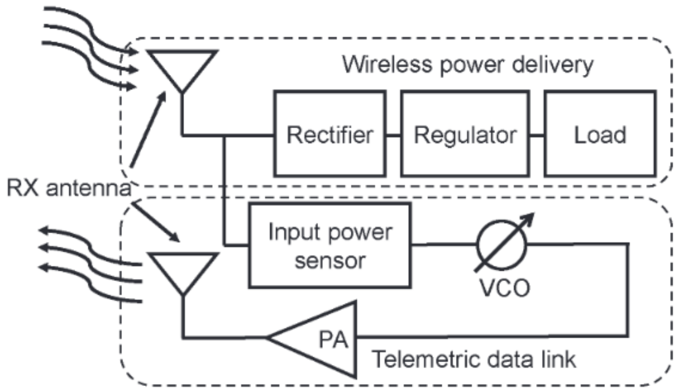


Selective, Tracking and Power Adaptive WPT System

- How to **acquire** and encode the WPT **Channel State Information**?

- Current approaches employ mechanisms to **sample** the signal's power level
  - ADC required
  - Processing and encoding
  - Vulnerable to transmission errors



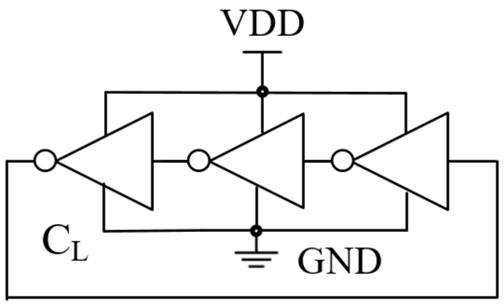


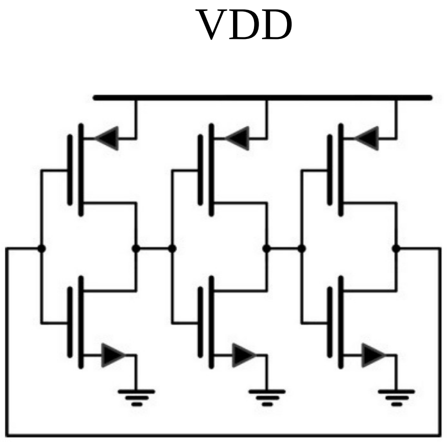
Y. Zou and S. O'Driscoll, "Implant Position Estimation Via Wireless Power Link," in *IEEE Trans. on Circ. and Syst.s II: Express Briefs*, vol. 62, no. 2, pp. 139-143, Feb. 2015.

Deviation from the ideal **real time** estimation and **energy consumption**!

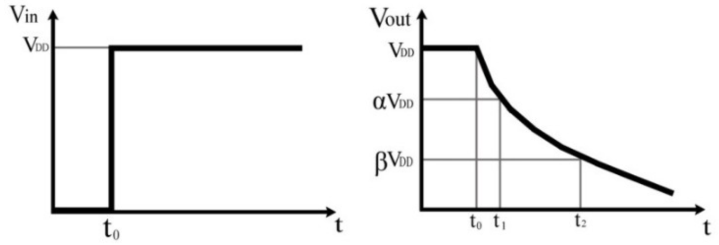
Selective, Tracking and Power Adaptive WPT System

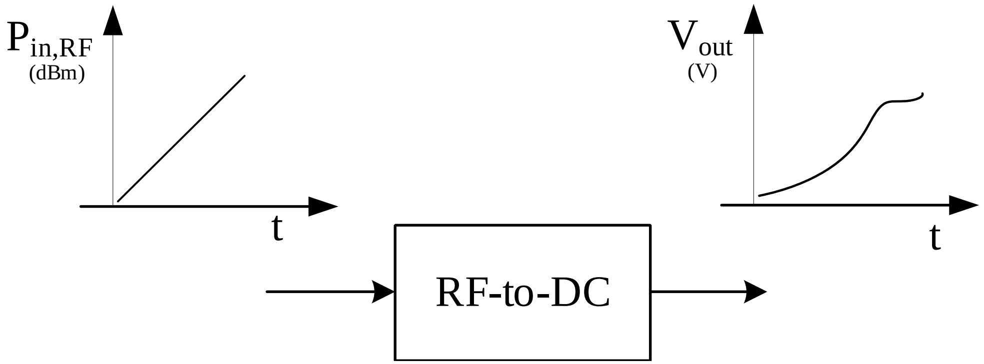
- **Voltage controlled ring oscillator**
  - Low cost
  - Small size
  - Very low power





$$f_0 = \frac{1}{2Ntd}$$





$$t_d \propto \frac{2C_L(1-\alpha)VDD}{\mu n\ Cox\frac{W}{L}(VDD-Vt)^2} + \frac{C_L}{\mu_n C_{ox}\frac{W}{L}(V_{DD}-V_{th})}\ln\left(\frac{2\alpha-\beta}{\beta}\right)$$

Selective, Tracking and Power Adaptive WPT System

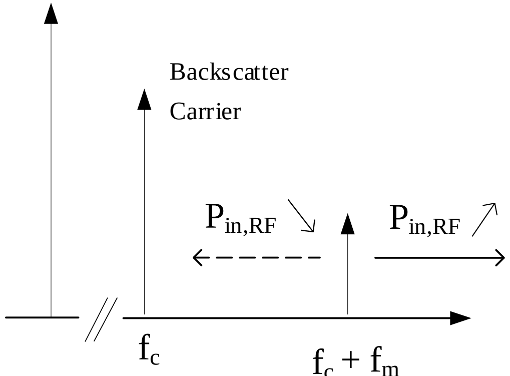
- Efficiency, given by

$$V_{out,dc} = \sqrt{\eta \cdot R_{Load} \cdot P_{in,RF}}$$

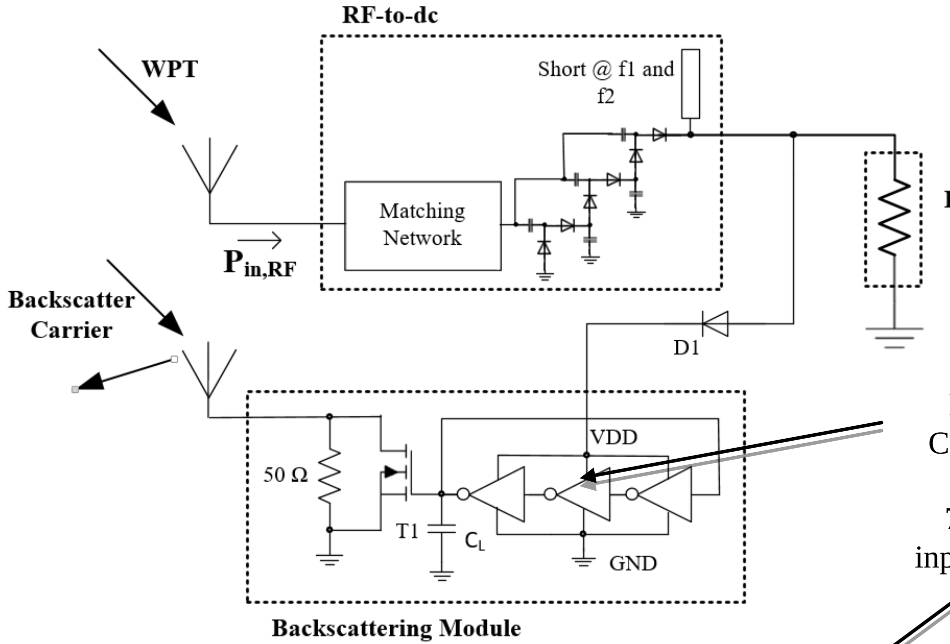
- **Gate delay** depends on the RF-to-dc output voltage

$$t_d = f\left(V_{out,dc}\right)$$

Thus, $t_d = g\left(P_{in,RF}\right)$

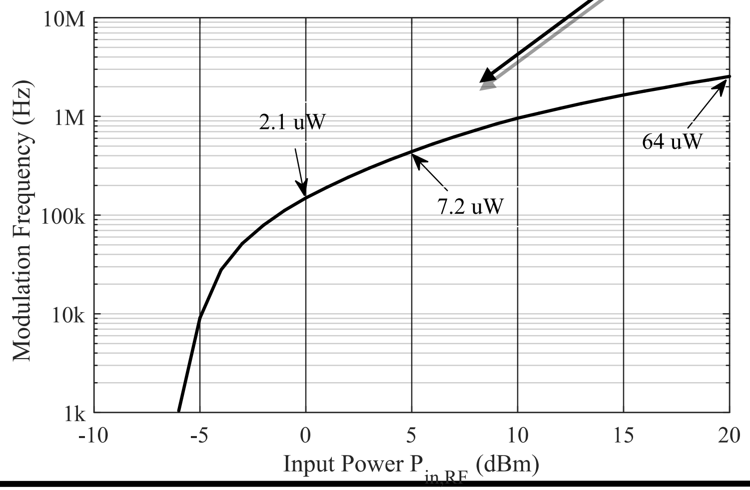


$$\boldsymbol{f_m = \frac{1}{2 N t_d} = \frac{1}{2 \cdot g\left(P_{in,RF}\right)}}$$



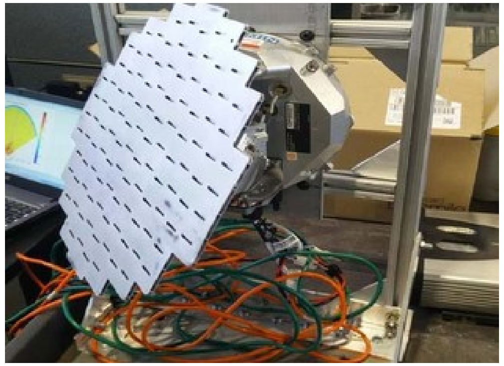
MM74HC04MX COTS Hex inverter

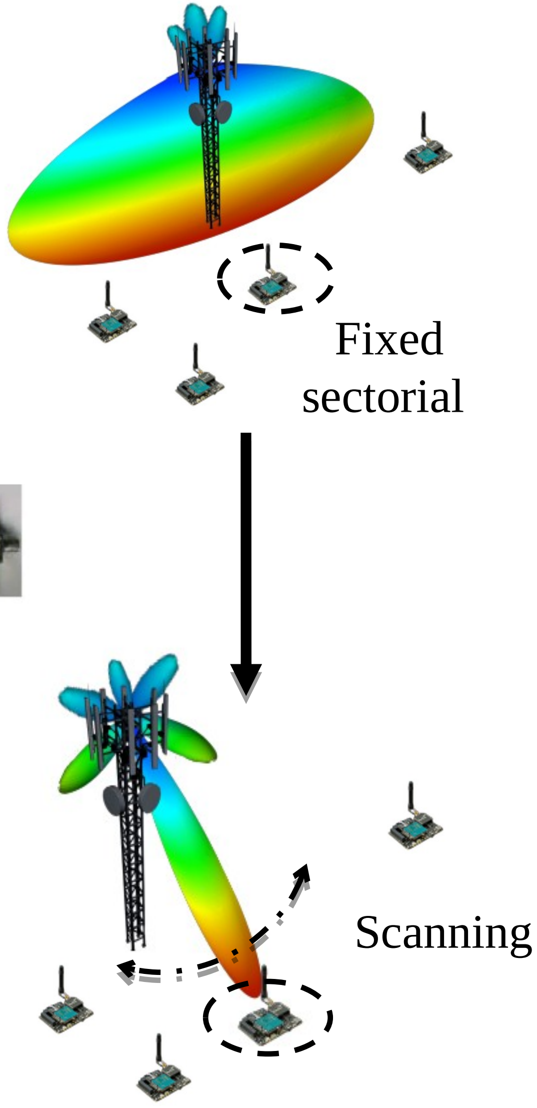
7.2 uW @ 5 dBm input power, 300 kHz

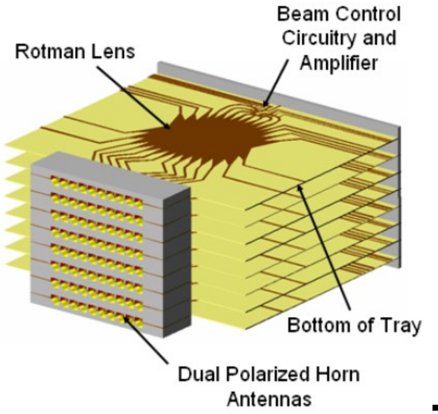


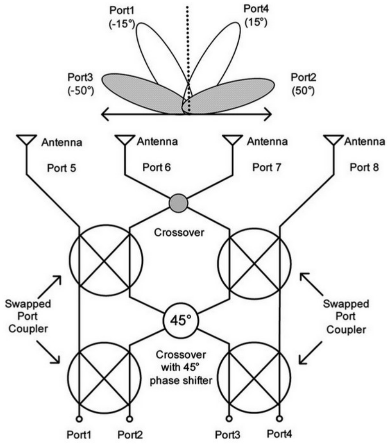
Selective, Tracking and Power Adaptive WPT System

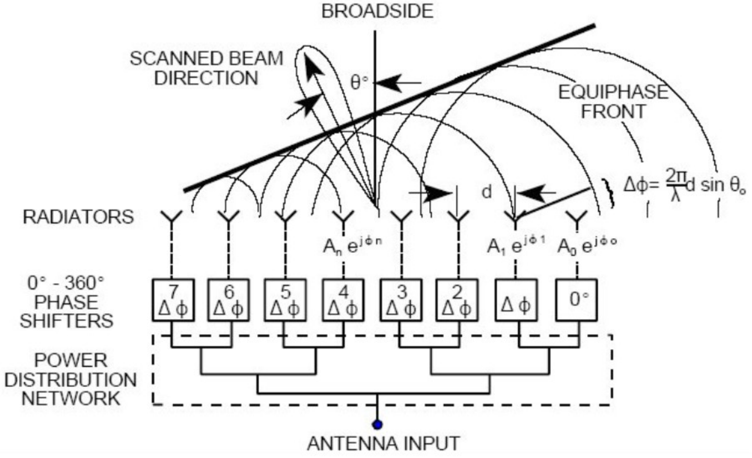
- How to **locate** the nodes?
- A **scanning** antenna is required
  - Mechanically
  - Leaky-Wave antenna
  - Rotman lens/Buttler matrices
  - Phased Array





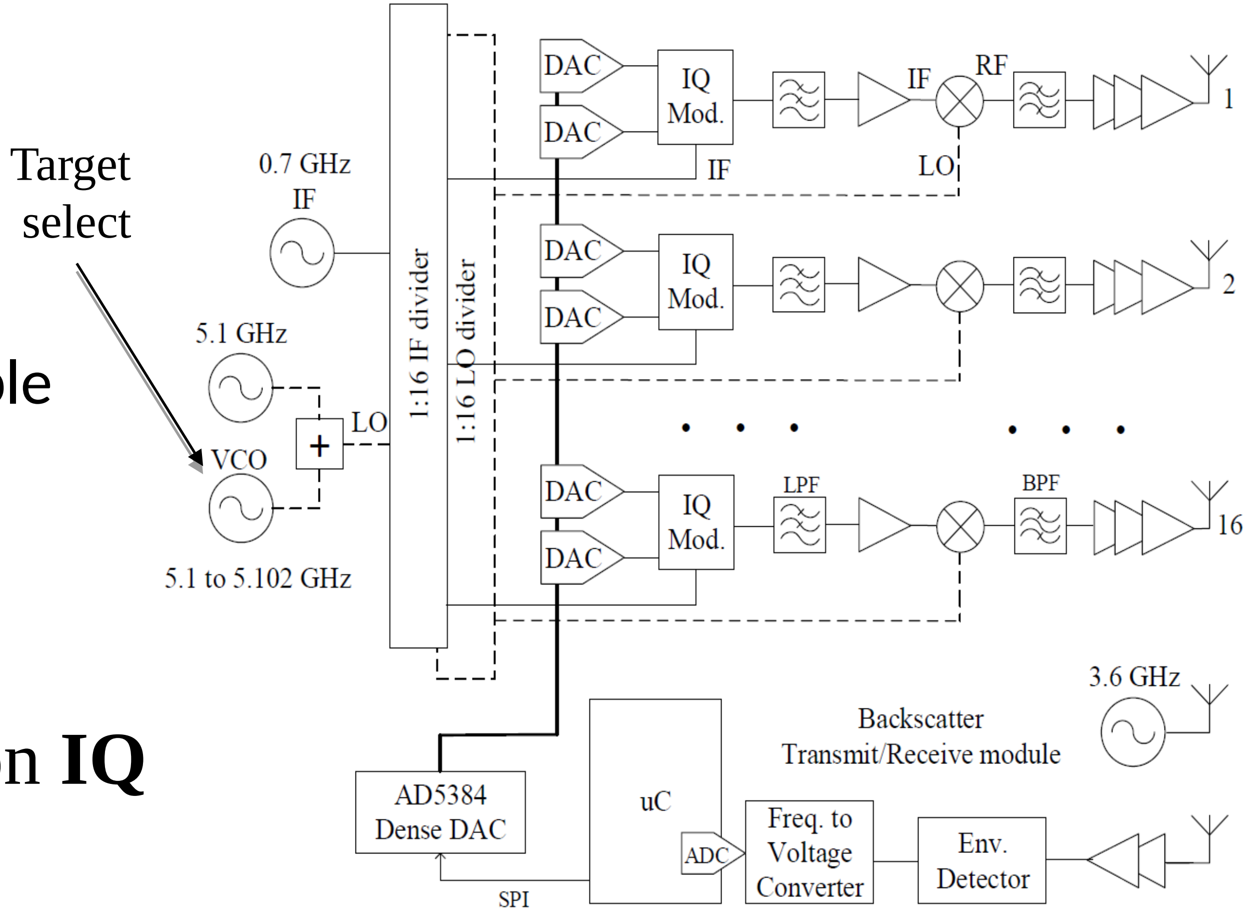






Selective, Tracking and Power Adaptive WPT System

- **Phased Arrays**
  - High beam agility
  - Arbitrary space scanning
  - Simultaneous generation of multiple beams
  - Failure of some components does not result in a complete system failure



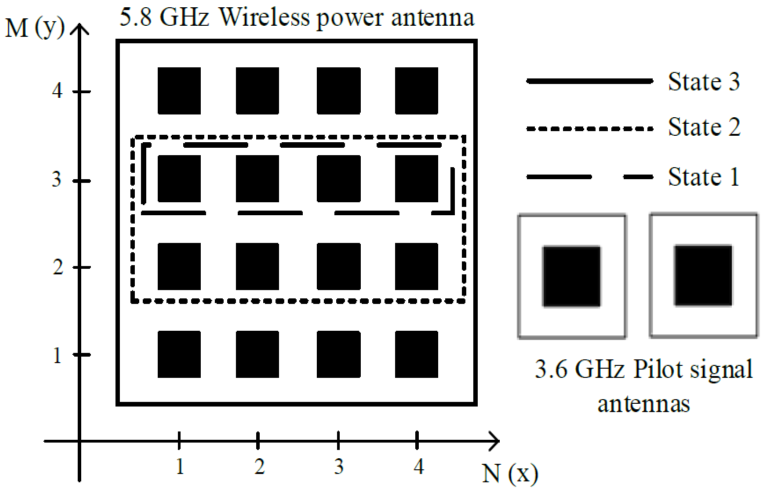
- 16-element phased array based on **IQ modulators**

$$\psi(n,m) = k\ d\ n \sin(\theta_p) \cos(\varphi_p) + k\ d\ m \sin(\theta_p) \sin(\varphi_p) \quad n = 1..N, m = 1..M$$

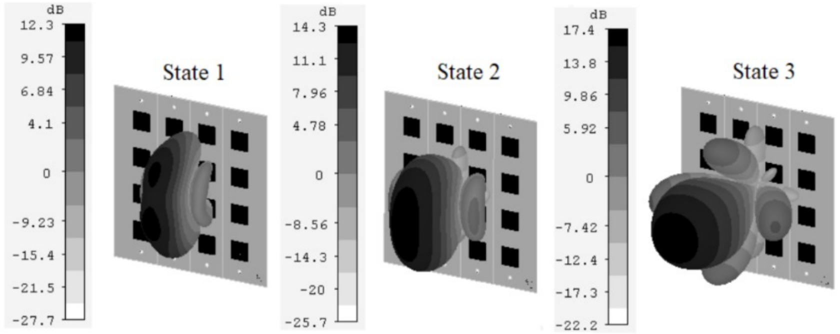
- **Backscatter transceiver** module to monitor the receiver's feedback

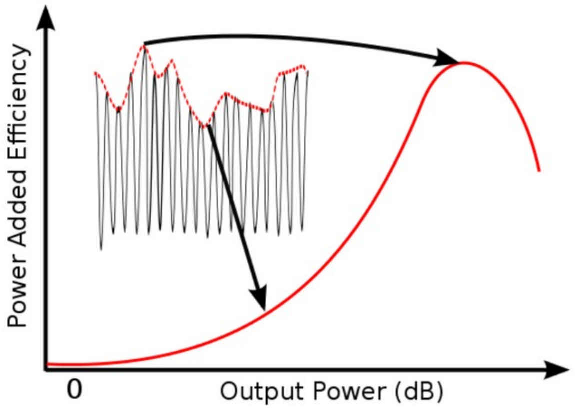
Selective, Tracking and Power Adaptive WPT System

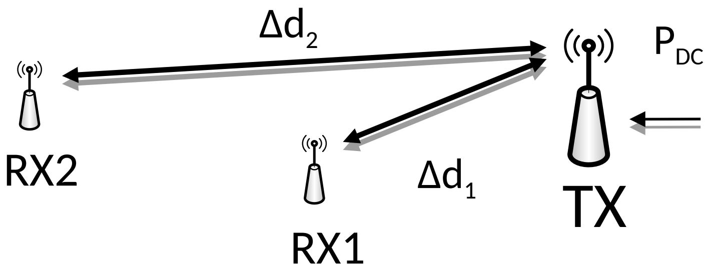
- 4x4 planar microstrip patch antenna array
- Operated with **N states**:
  - Number of possible states may be equal to the number of elements
  - Elements completely **Off** or in **Saturation**



$$EIRP_n = n\,EIRP_1 \text{ and } P_{DC,n} = \frac{n}{P_{DC,N}}$$





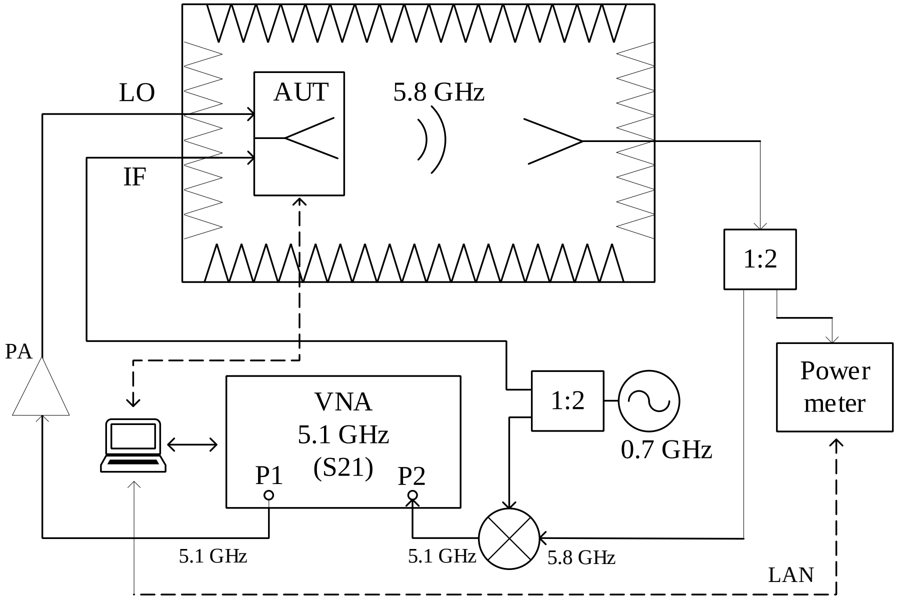


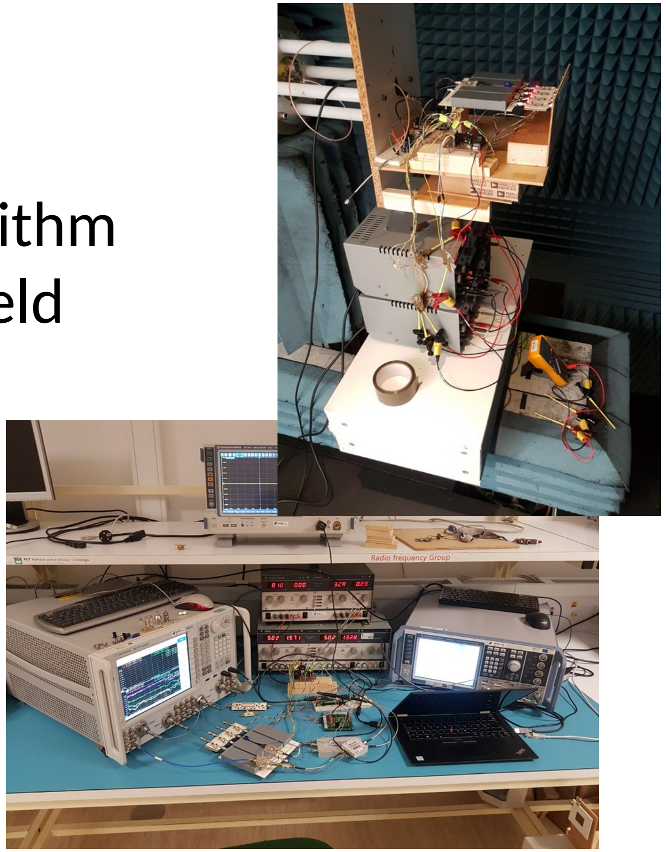
D. Belo, R. Correia, P. Pinho, and N. B. Carvalho, "Enabling a constant and efficient flow of wireless energy for IoT sensors," IEEE MTT-S Int. Microw. Symp. (IMS), Honololu, HI, pp. 1342-1344, Jun. 2017.

Selective, Tracking and Power Adaptive WPT System

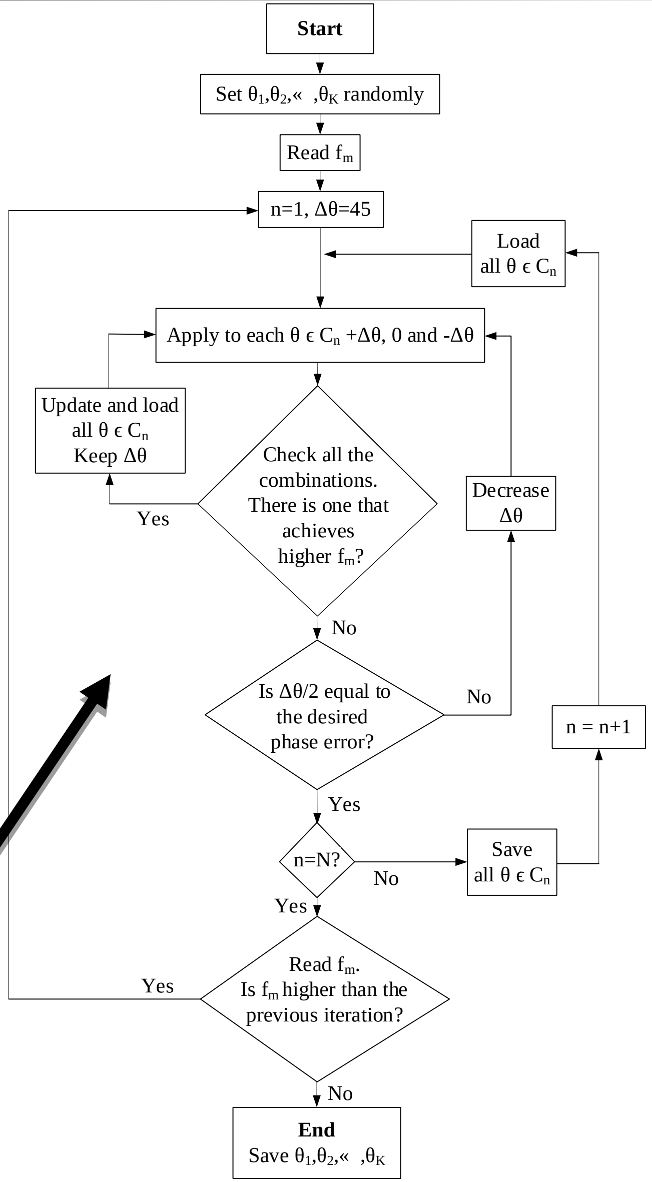
- **Calibration**

Phase-Perturbation based algorithm and measurements of the far-field received signal strength

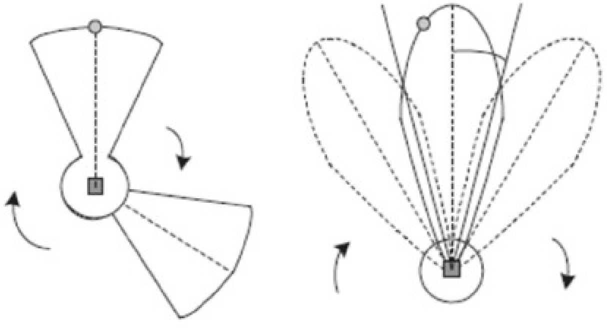




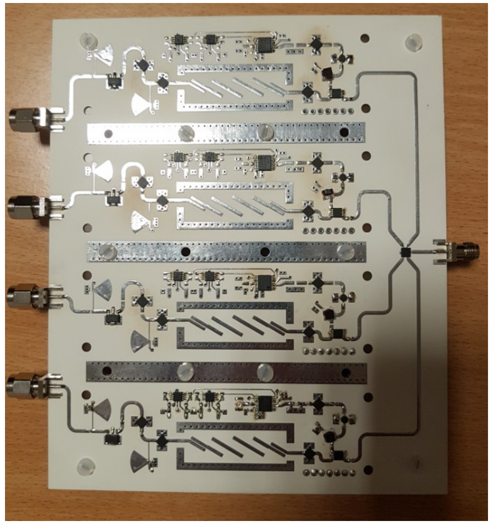
RSSI feedback - calibration can be done **in situ…**

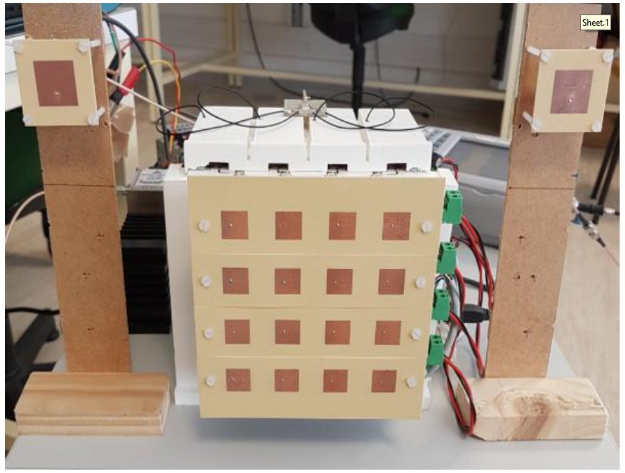


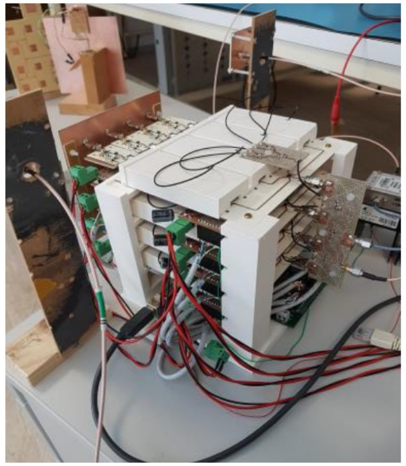
Selective, Tracking and Power Adaptive WPT System

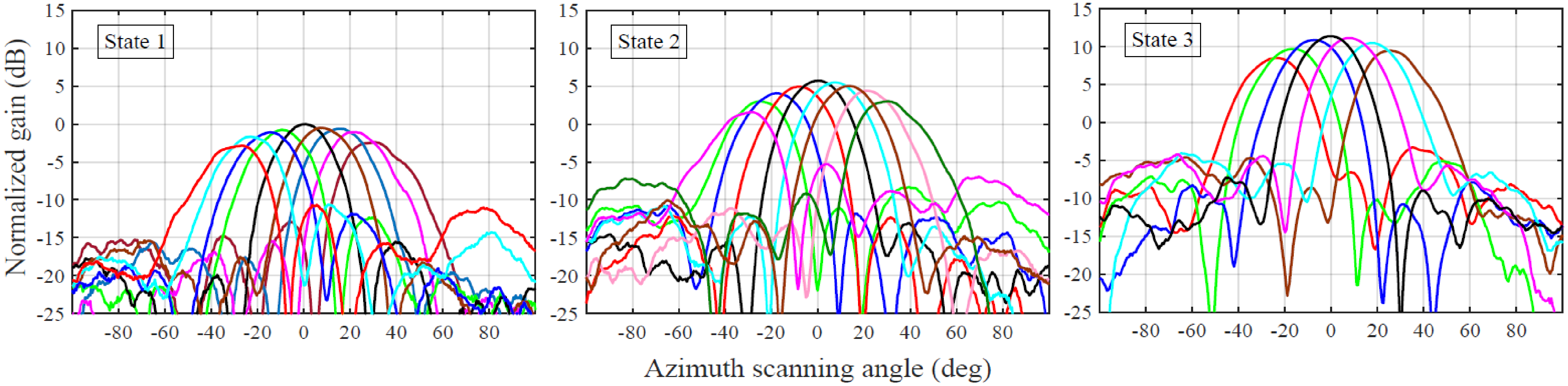


Beamsteering   Beamswitching





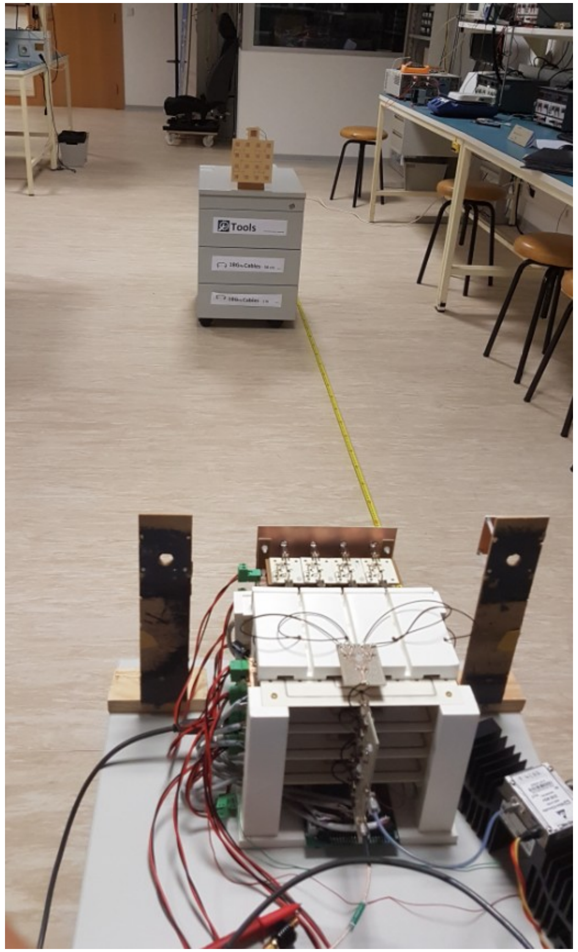




Selective, Tracking and Power Adaptive WPT System

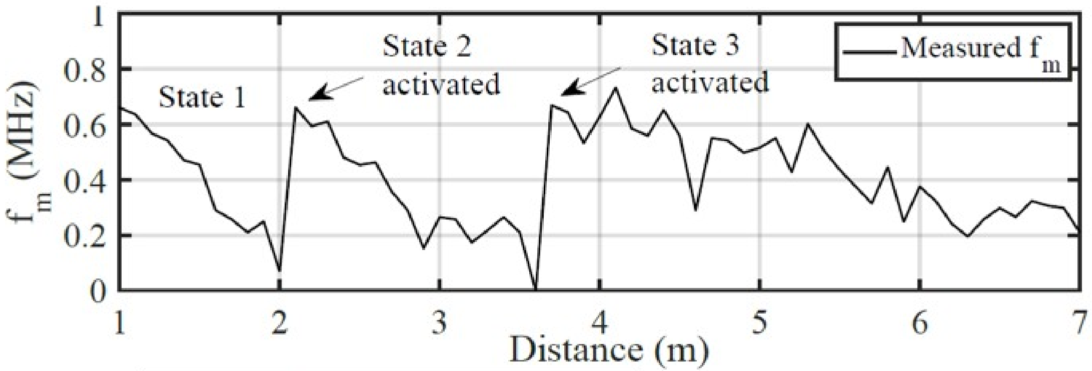
- **Link budget** measurements

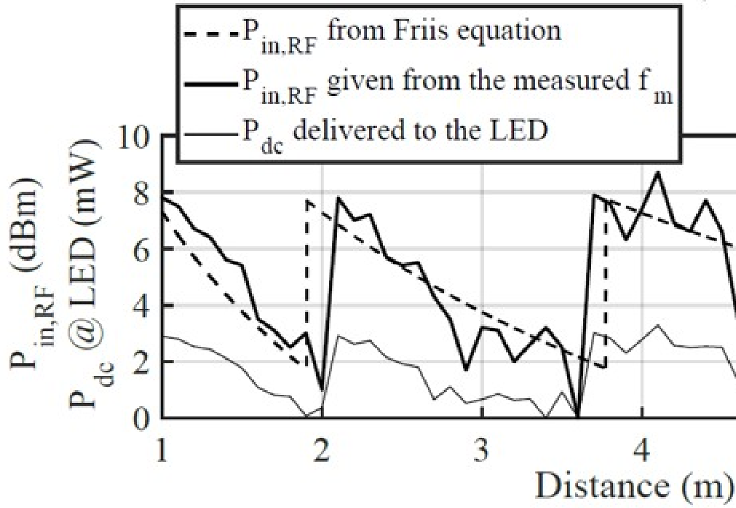
Node 1



Remember that and are interchangeable quantities!

	Nº of Antenna elements	P_t (dBm/tone)	Estimated G_t (dBi)	Estimated G_r (dBi)
State 1	*4*	*25*	*12.3*	
State 2	*8*	*28*	*14.3*	*17*
State 3	*16*	*31*	*17.4*	
Pilot Signal	*1*	*25(CW)*	*6*	



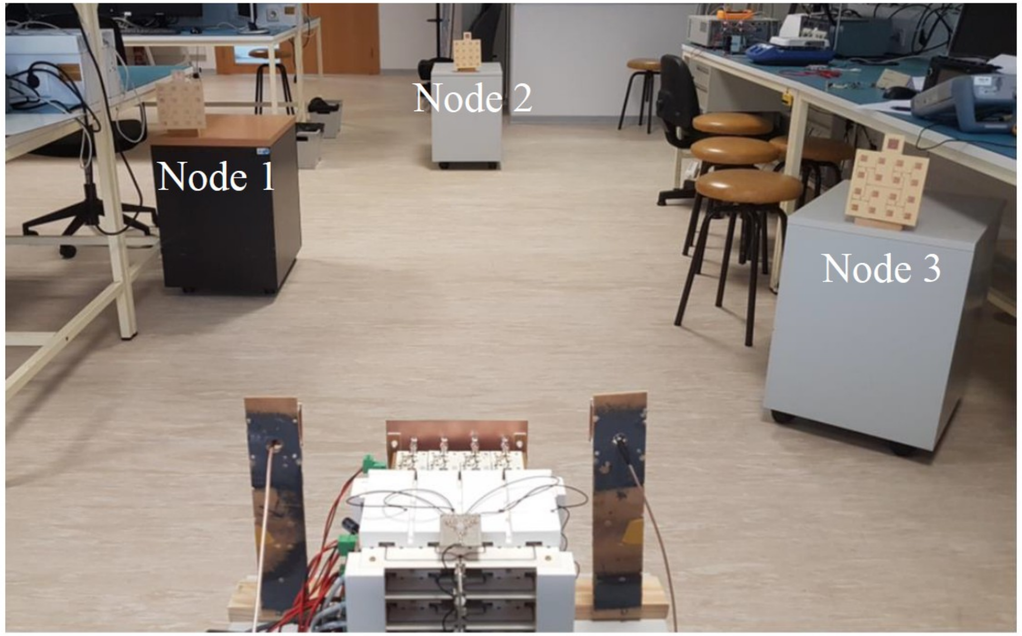


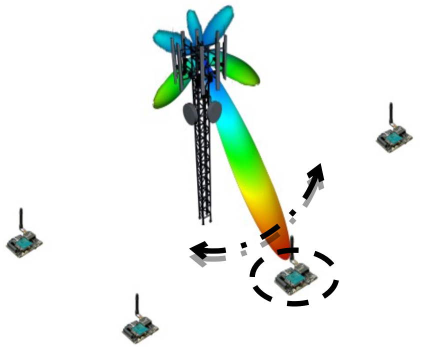
$$P_{in,RF} = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

Selective, Tracking and Power Adaptive WPT System

- The system operates as follows:

1. Set the required signal to activate the desired target;
2. Scan with all elements activated;
   If the desired target is present, it will instantaneously activate its backscatter modulator
3. Adapt the transmitted power (state) to keep the node awake with the minimum required power





D. Belo, D. C. Ribeiro, P. Pinho and N. Borges Carvalho, "A Selective, Tracking, and Power Adaptive Far-Field Wireless Power Transfer System," in IEEE Trans. on Microw. Theory and Tech., vol. 67, no. 9, pp. 3856-3866, Sept. 2019.

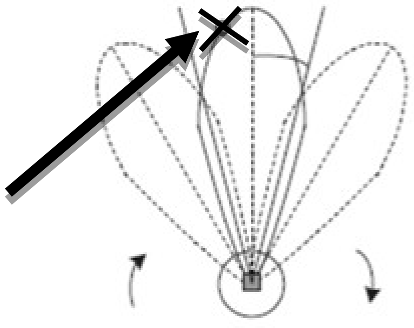
Selective, Tracking and Power Adaptive WPT System

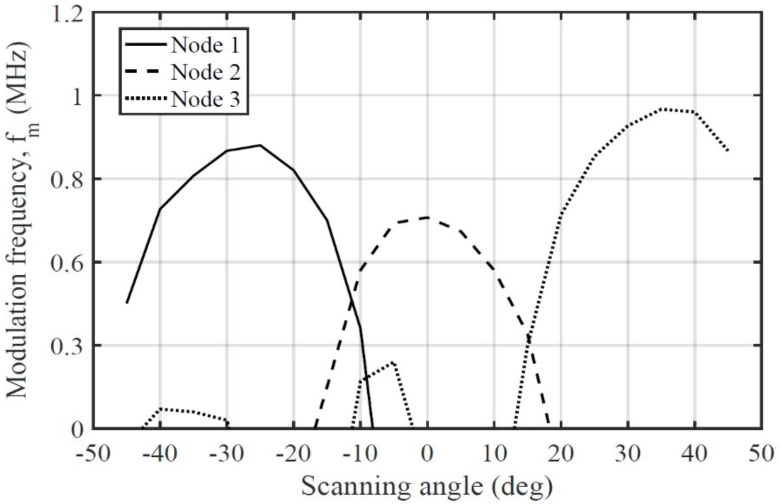
- Each scan always provide **the best direction** to send the energy

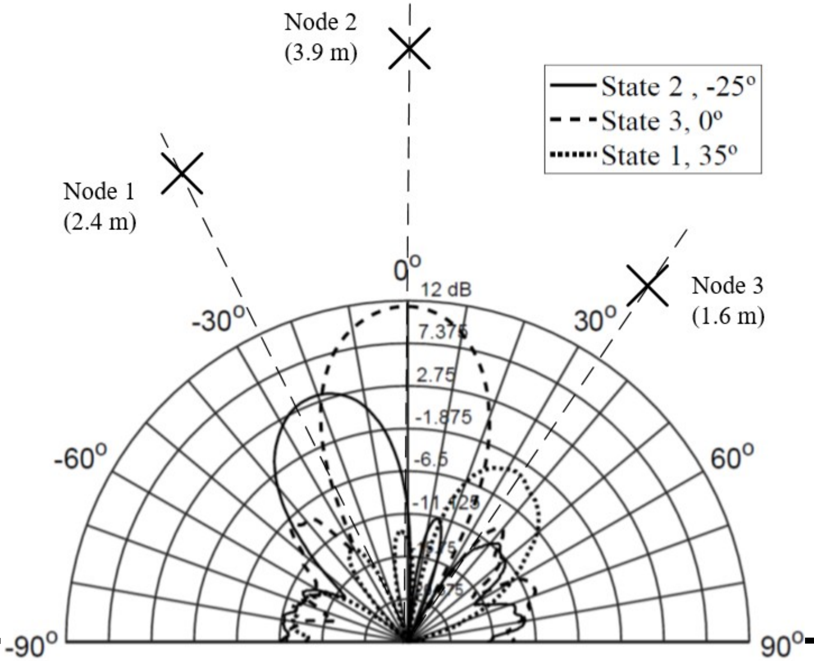
- **Accurate RSSI**

- **High SNR**

Target







- Anechoic chamber calibration - Only a rough estimation

⇒ It is supposed that one of the possible beams will turn on the target which is afterwards **fine-tuned** to achieve **perfect align**

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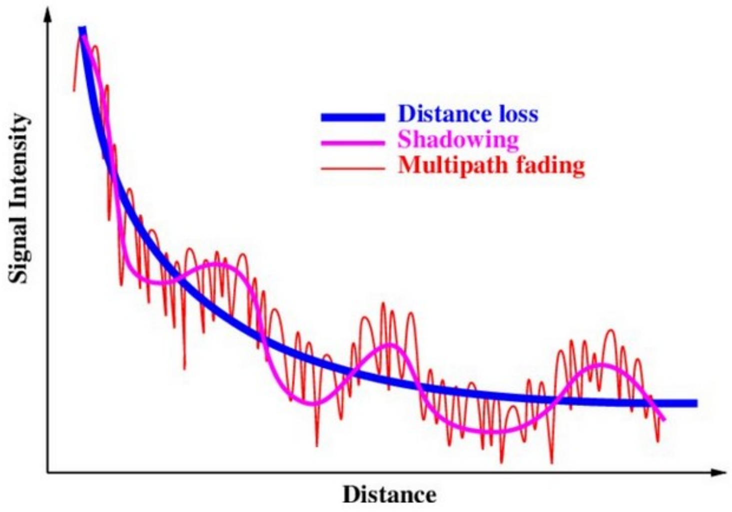
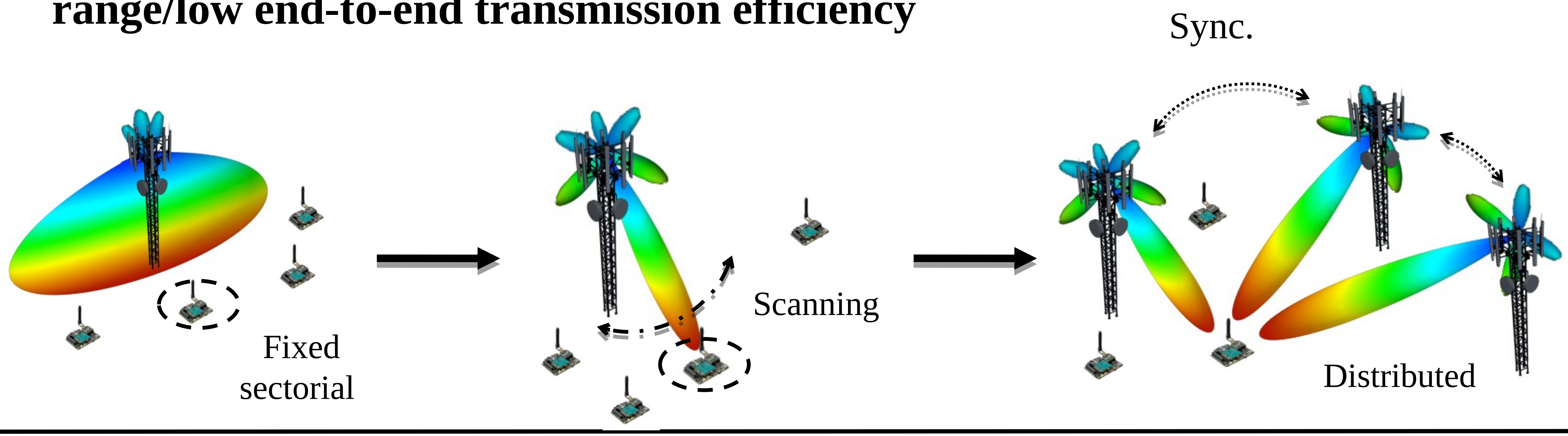
Phase Synchronization for Distributed WPT

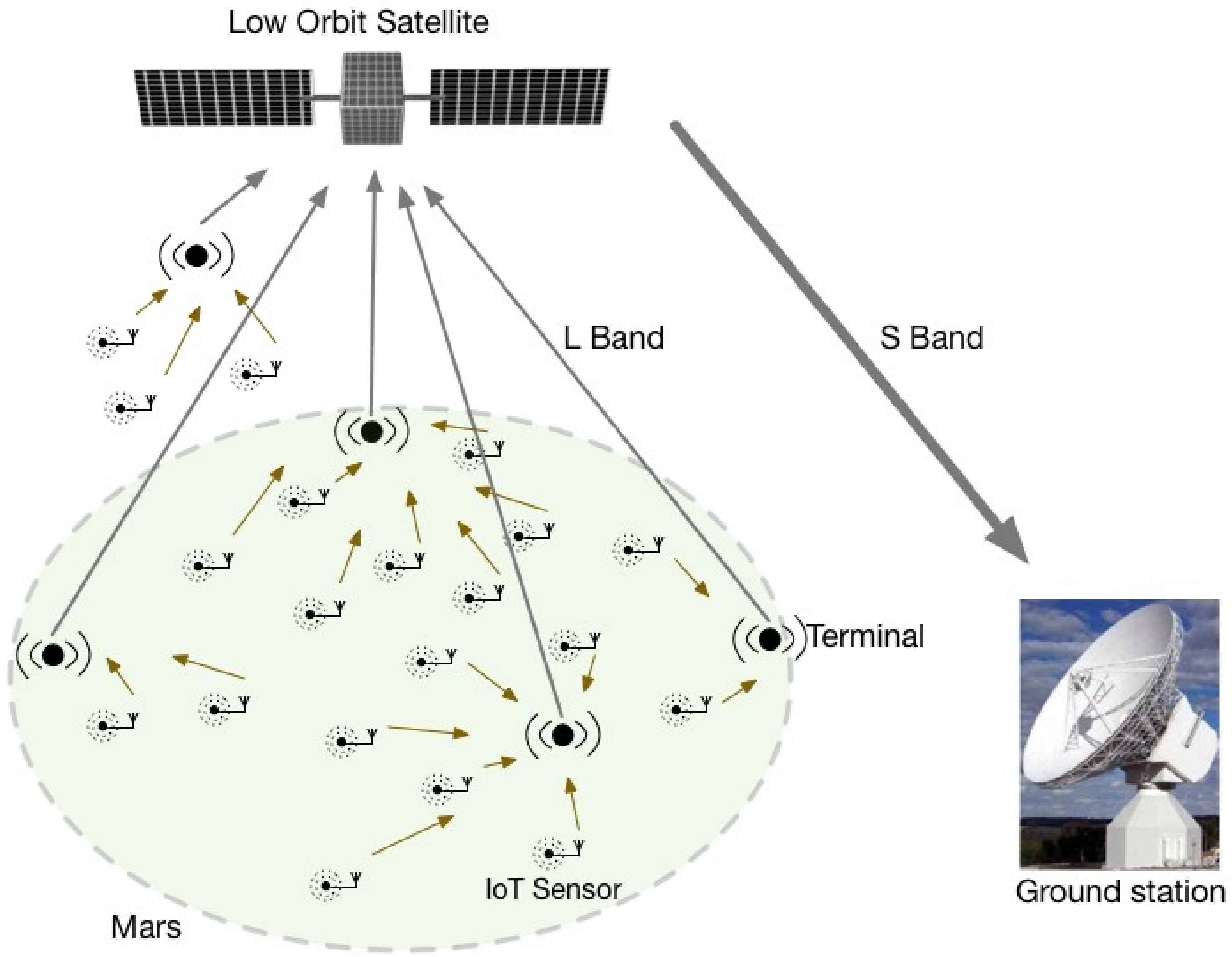
- WPT experience from propagation losses as well as shadowing and multipath/fading effects



Performance degradation/reduced covering range/low end-to-end transmission efficiency



Developing a Deep Space Sensor IoT



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Questions?

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https://www.hindawi.com/journals/wpt/

IEEE WPT

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Rui Fiel
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João Santos

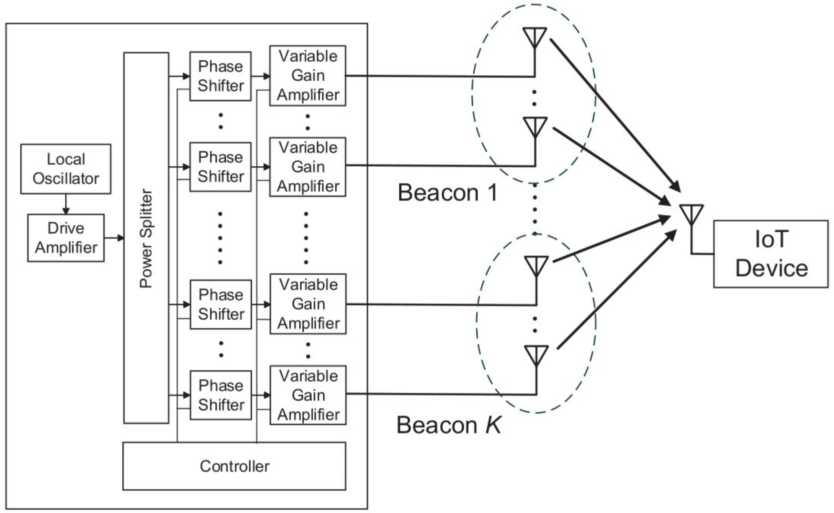
3. Radiative Far-Field WPT

ii. Phase Synchronization for Distributed WPT

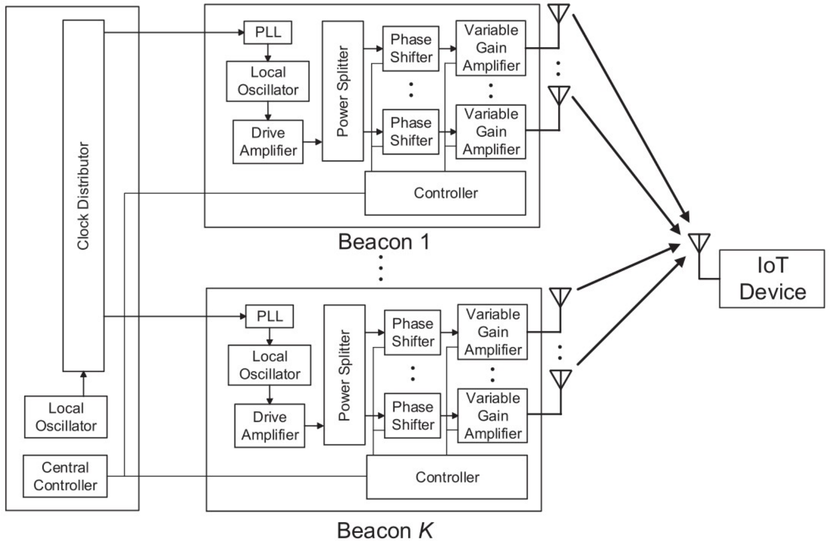
ii. Phase Synchronization for Distributed WPT

- Less power is wasted in overcoming penetration and shadowing losses
- However, in **fully distributed** scenarios, new **challenges** arise

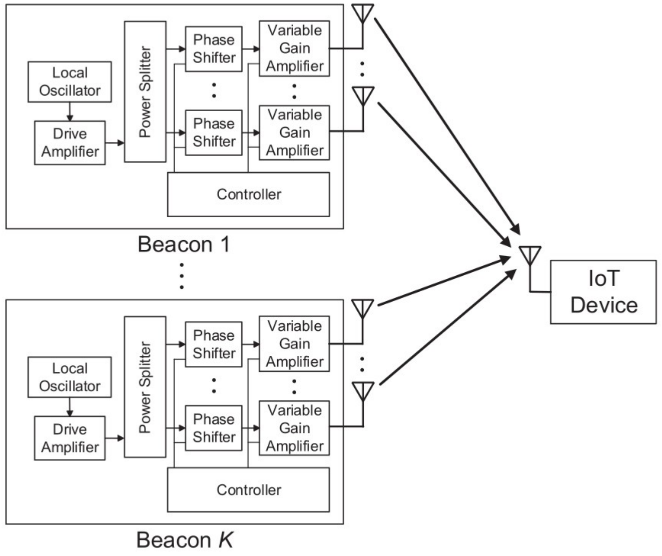
Centralized



Semi-distributed



Fully distributed

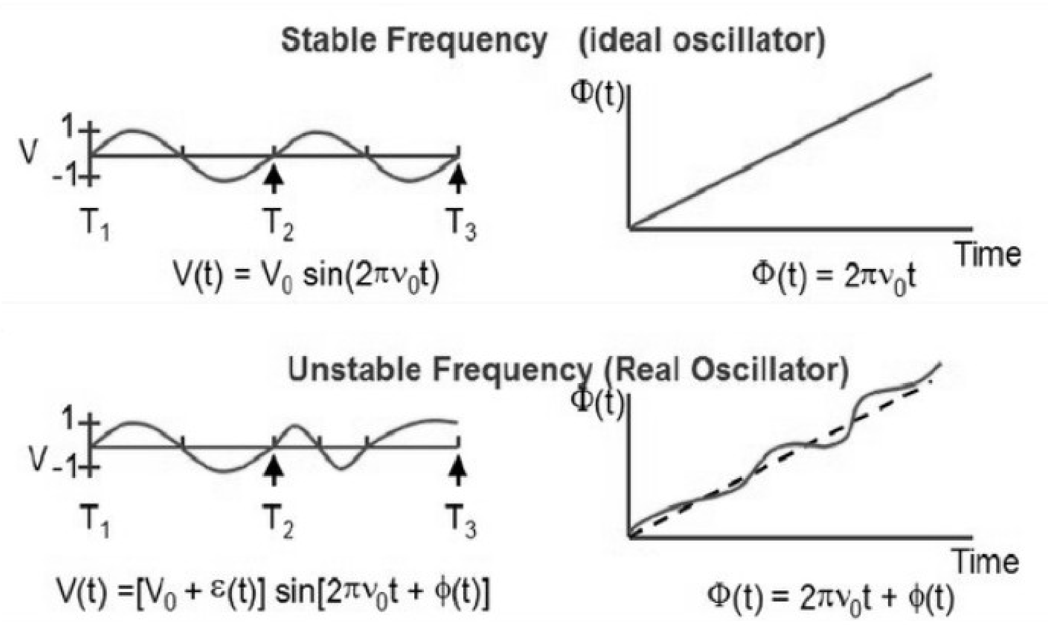


K. W. Choi, A. A. Aziz, D. Setiawan, N. M. Tran, L. Ginting and D. I. Kim, "Distributed Wireless Power Transfer System for Internet of Things Devices," in *IEEE Internet of Things Journal*, vol. 5, no. 4, pp. 2657-2671, Aug. 2018.

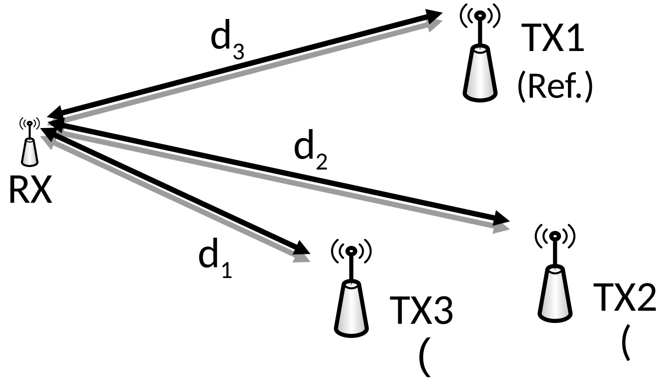
ii. Phase Synchronization for Distributed WPT

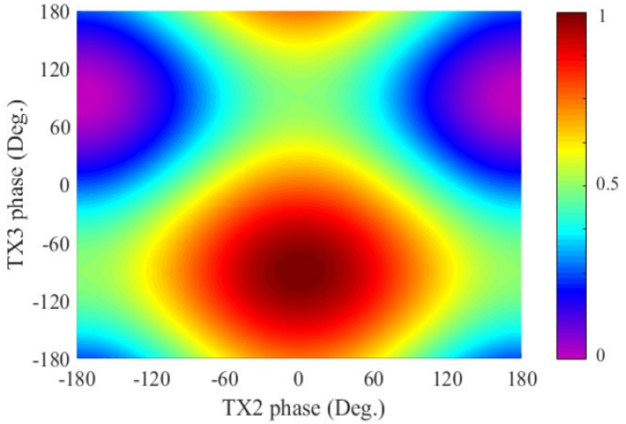
- **Frequency Synchronization**
  - Centralized
  - Semi-distributed – PLLs
  - Fully distributed – Troublesome

Synchronize to a broadcasted reference signal...



- **Phase Synchronization**
  - **Not possible to achieve if not frequency synchronized**
  - Each method may be applied equally to all architectures



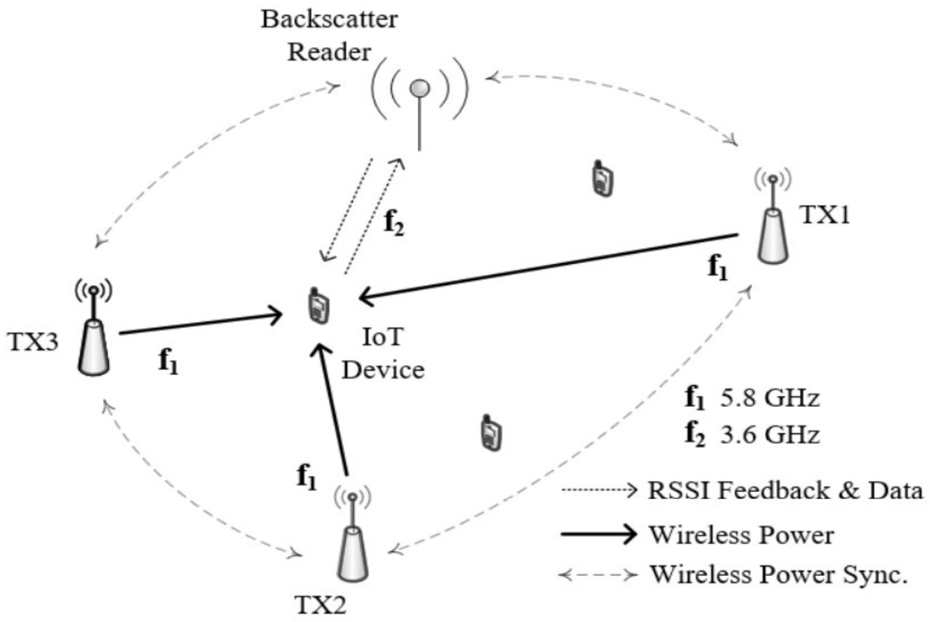


ii. Phase Synchronization for Distributed WPT

- **Phase Synchronization**

Relies on the availability of a **Channel State Estimator**

- The proposed receiver is suitable for such application!

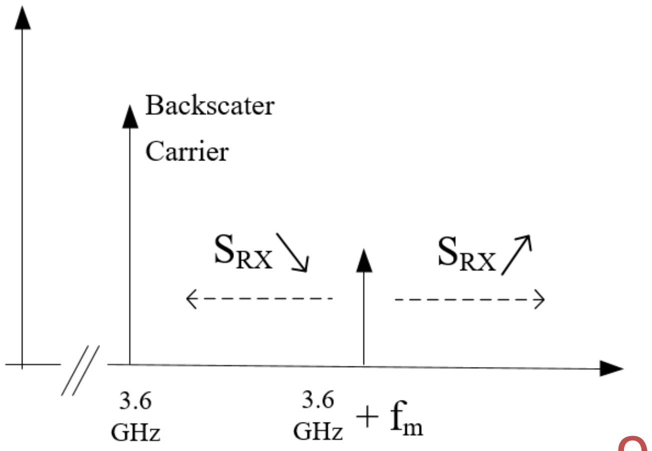


$$s_{TX,k}(t) = x_k(t)cos(2\pi f_c t + \theta_k)$$

$$s_{RX}(\psi_k, t) = x_k(t)\sum_{k=1}^{K} h_k \cos(2\pi f_c t + \psi_k)$$

$$\psi_k = \theta_k + \frac{2\pi f_c d_k}{c}$$

Find ,…, that maximizes the received power

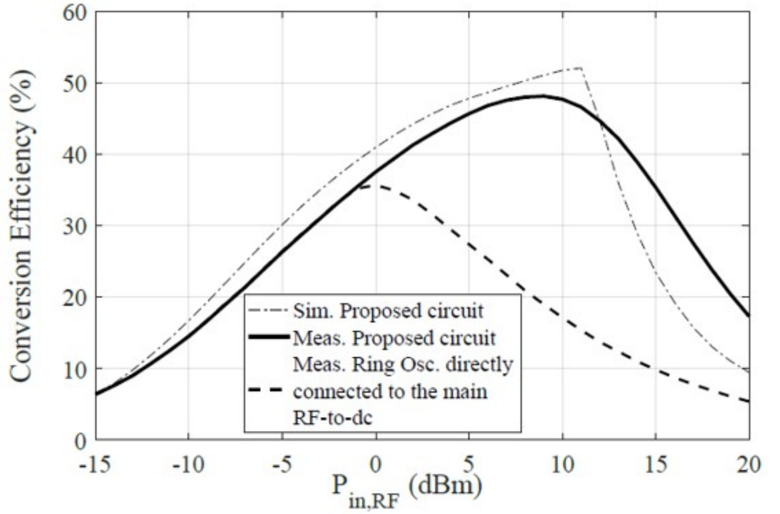


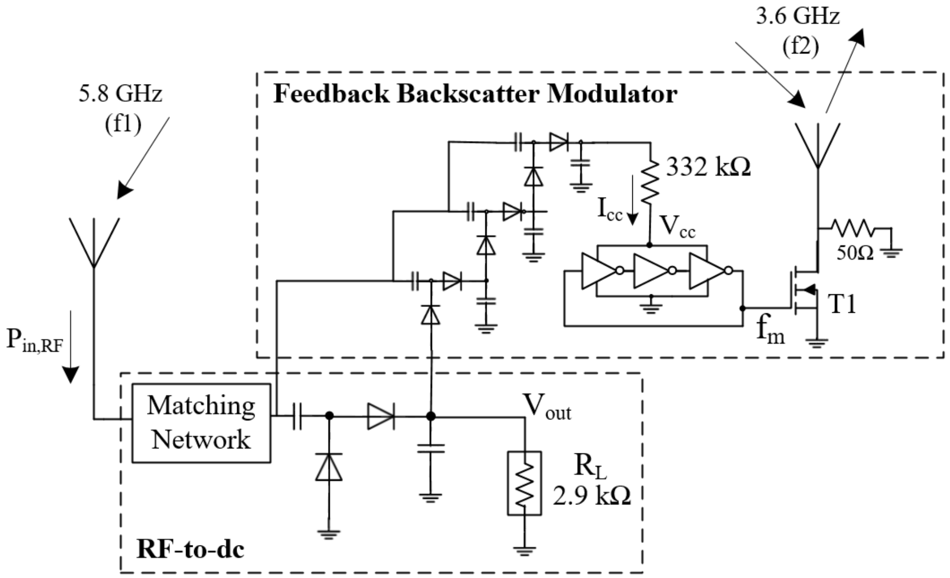
ii. Phase Synchronization for Distributed WPT

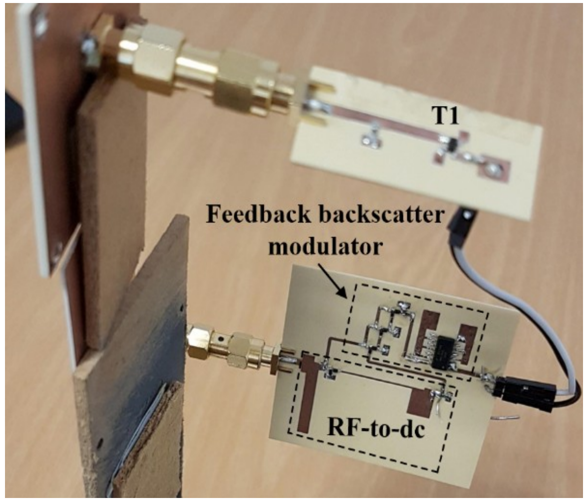
- Device improvements and optimization
  - **Auxiliary RF-to-dc converter (Voltage booster)**

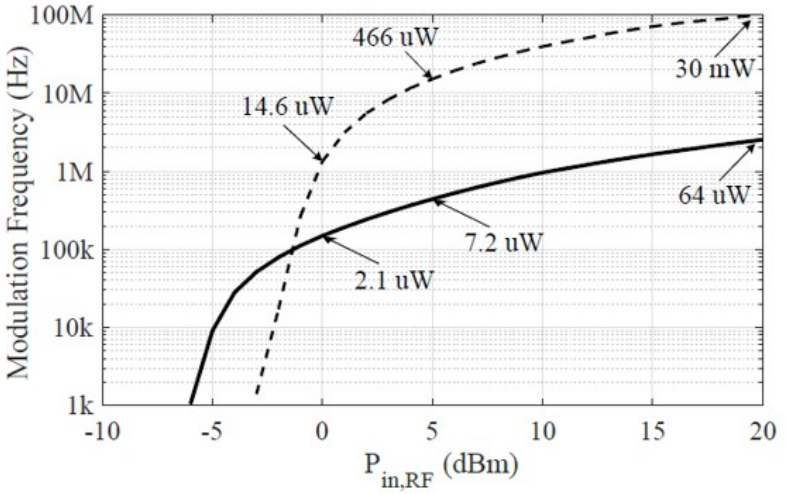
    Higher sensitivity

    Less power consumption



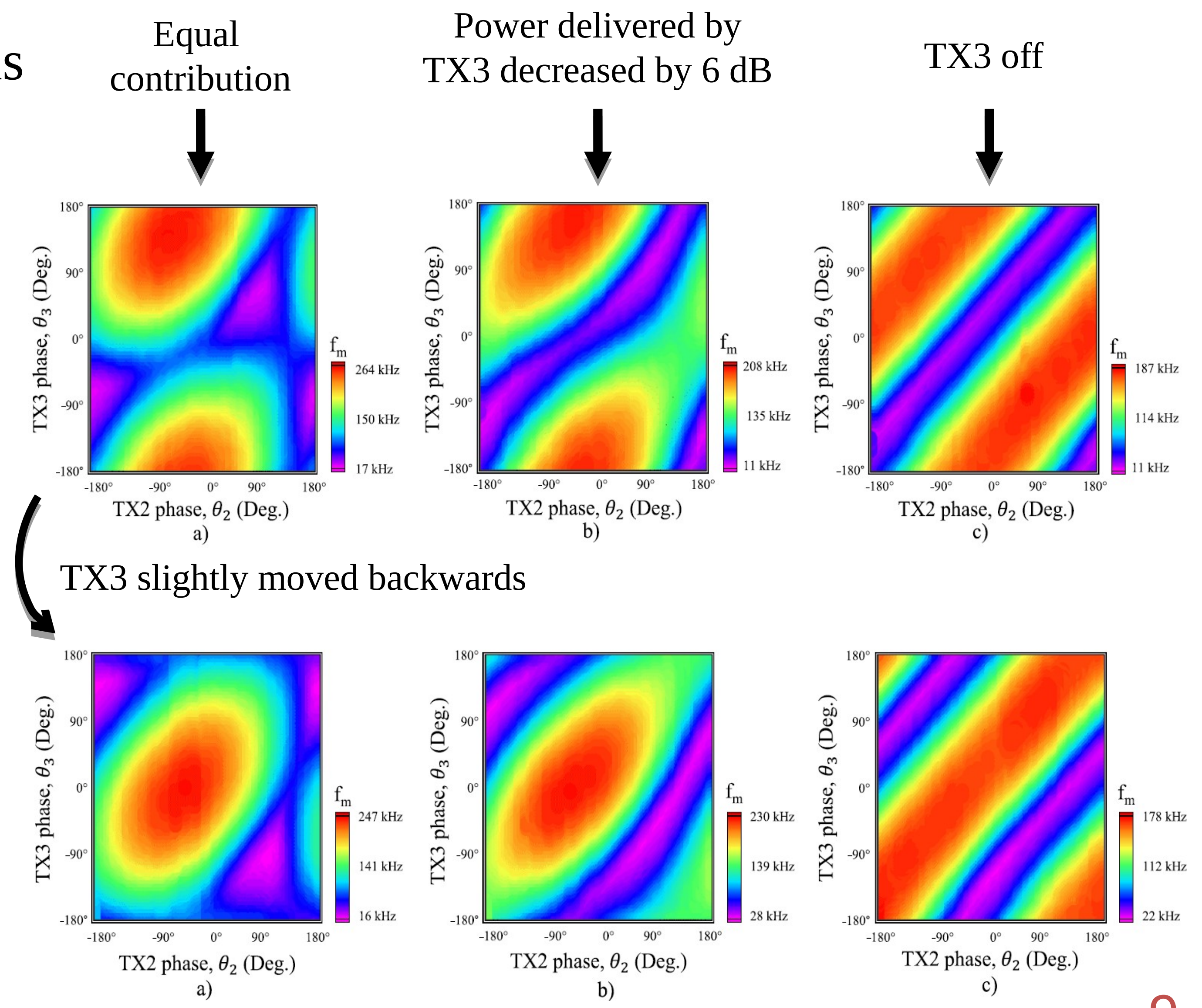






ii. Phase Synchronization for Distributed WPT

- Experimental received power versus TX phases
- **TX1** (Ref.), **TX2** () and **TX3** () @ 5.8 GHz
- Frequency synchronized through a common 10 MHz reference signal



ii. Phase Synchronization for Distributed WPT

- **Closed-loop phase synchronization**

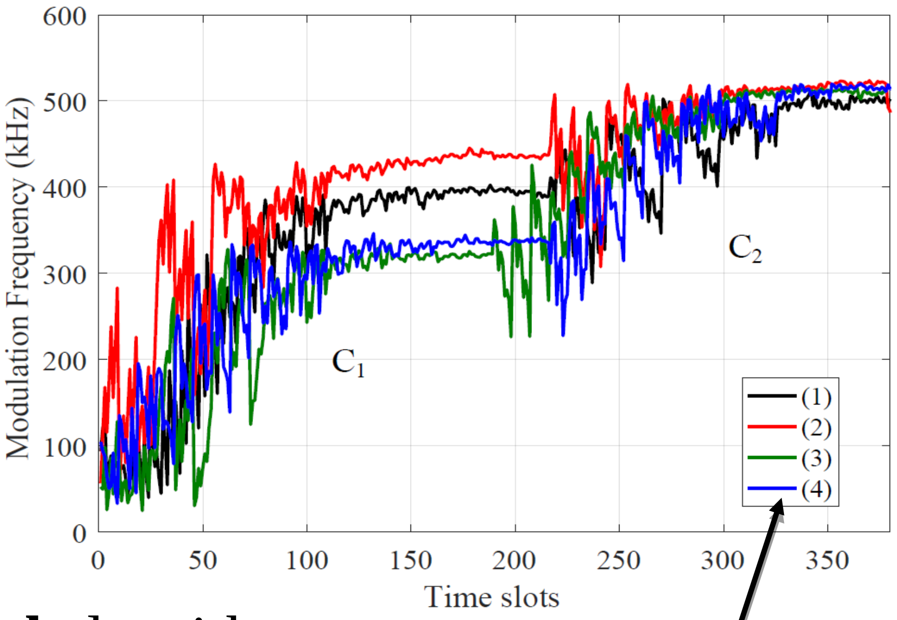
- **7** Transmitters

TX1 – **Ref.**

TX2, TX3 and TX4 – **Cluster 1**

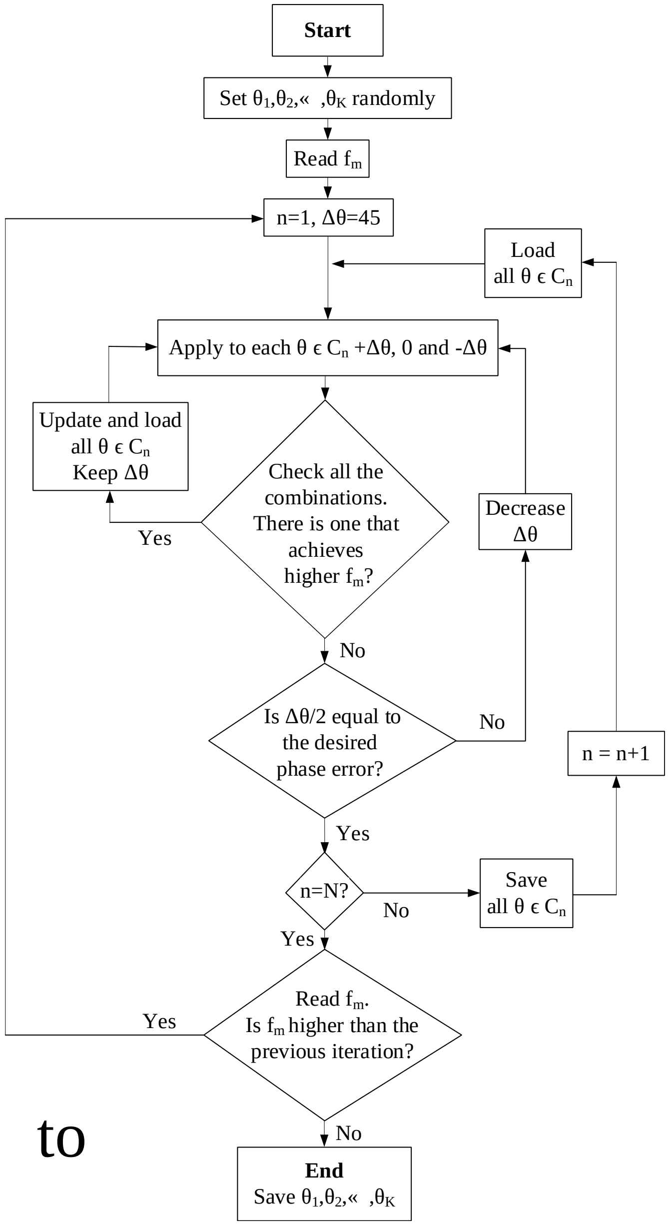
TX5, TX6 and TX7 – **Cluster 2**

CW @ 5.8 GHz



Different initial phases

- **Phase Perturbation-based** algorithm
- Perturbations progressively **fine-tuned**
- Clusters are **sequentially** and **iteratively** tuned in order to converge for the optimum solution



What about Multisines?