SIMULTANEOUS WIRELESS BACKSCATTER AND POWER TRANSFER

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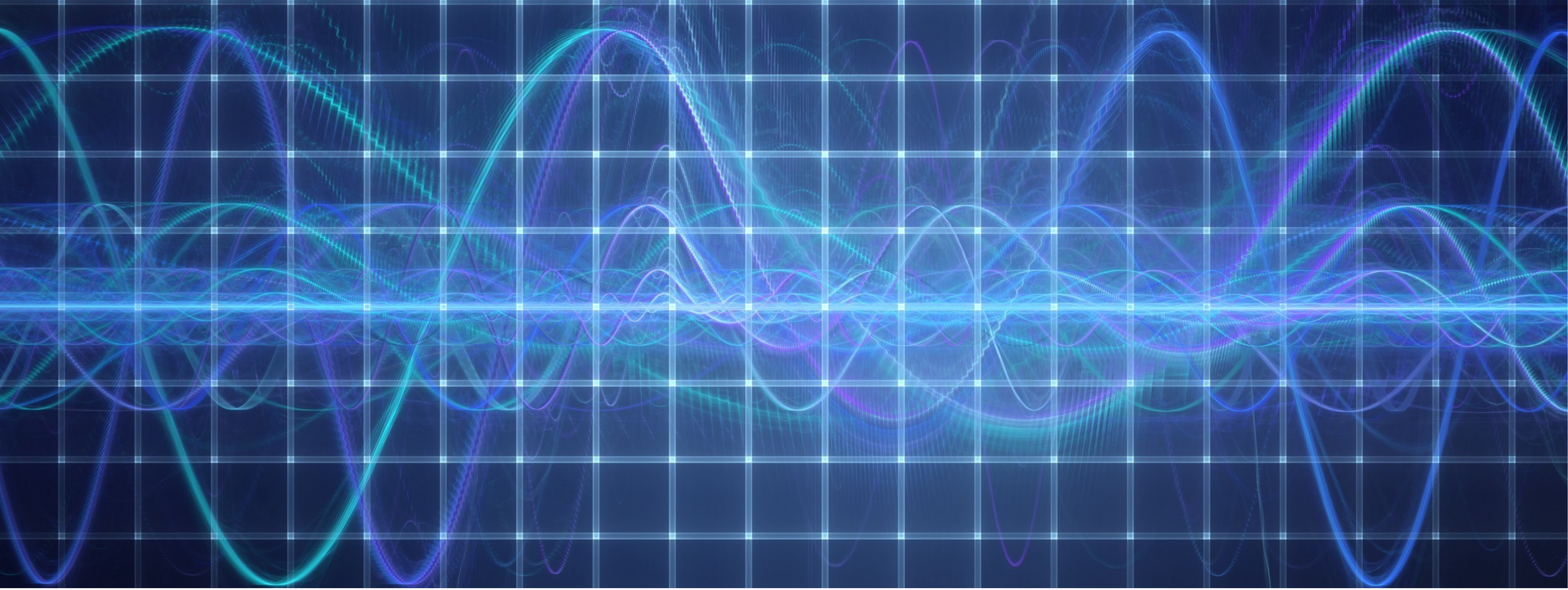
radio systems

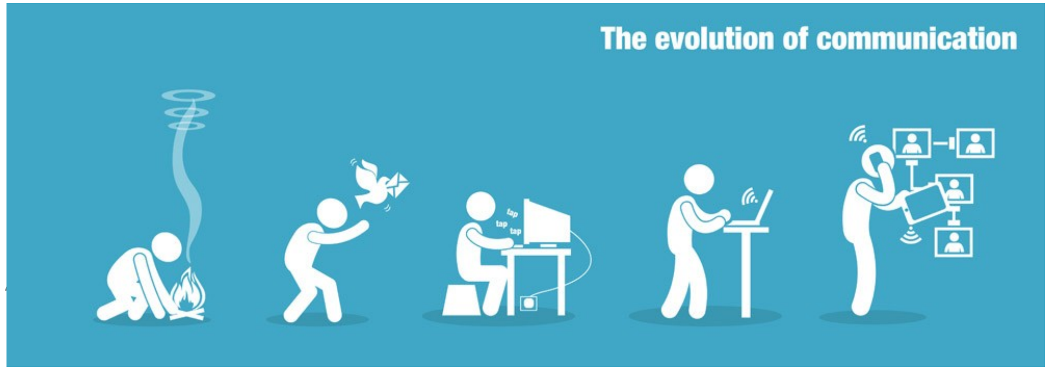
instituto de telecomunicações

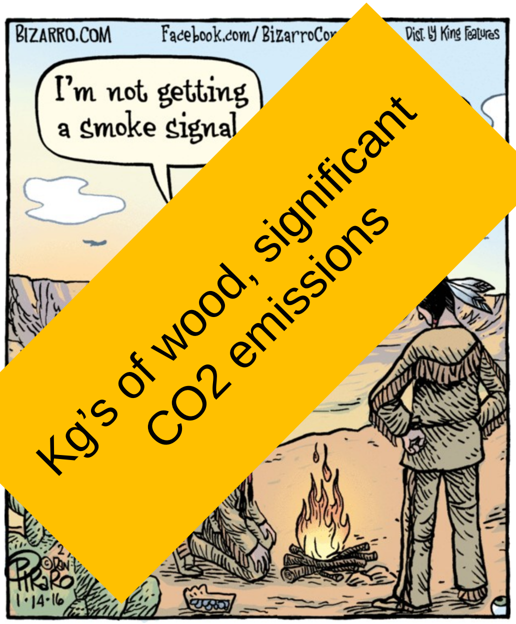


ENERGY IN COMMUNICATIONS

How much Energy I need to comunicate?

MOTIVATION COMMUNIC





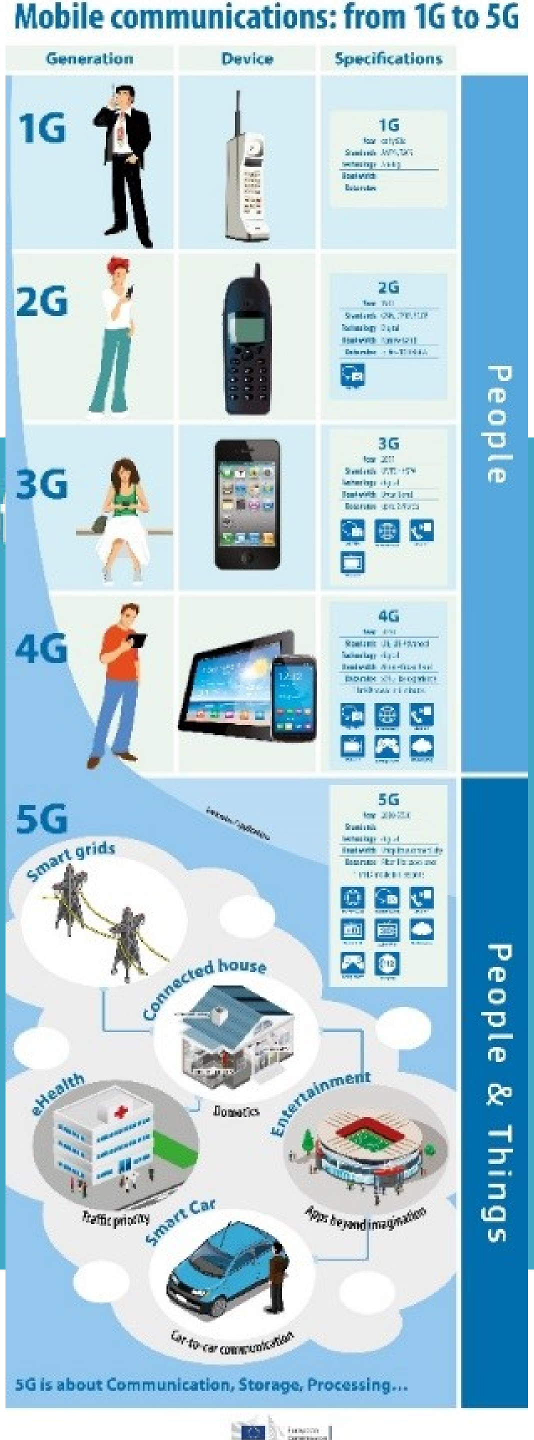
Kg's of wood, significant CO2 emissions

Kg's of corn, significant losses

Pre historical smoke signals burning wood

Carrier pigeons corn

MOTIVATION COMMUNICATIONS



IOT-IOE WIRELESS THINGS

Low bit Rate

- Low Power
- Low complexity

High bit Rate

- High Power
- High complexity

MOTIVATION ENERGY FOOTPRINT

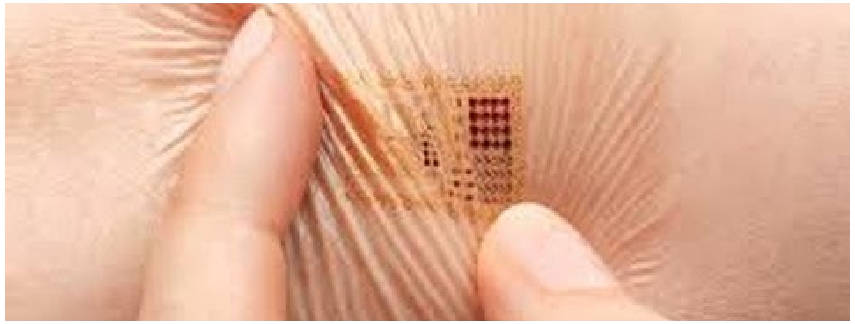
The bright Smart Future ….

Battery Waste

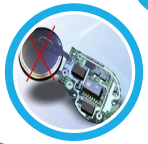
Huge Amount of Disposals

Large Amount of Energy

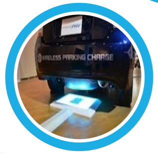
IOT WIRELESS THINGS



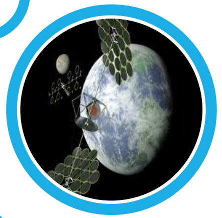
5G



Battery-less Sensors for health applications



Car Energy Collector



High Efficient Energy Collection

RFID's

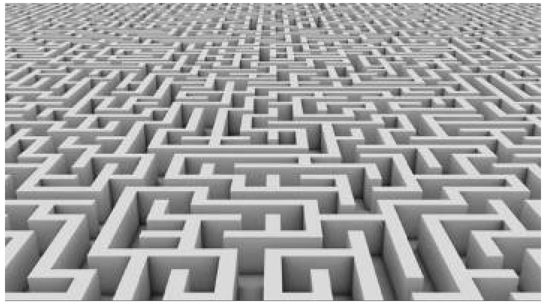
Domestic Appliances Wireless Energized

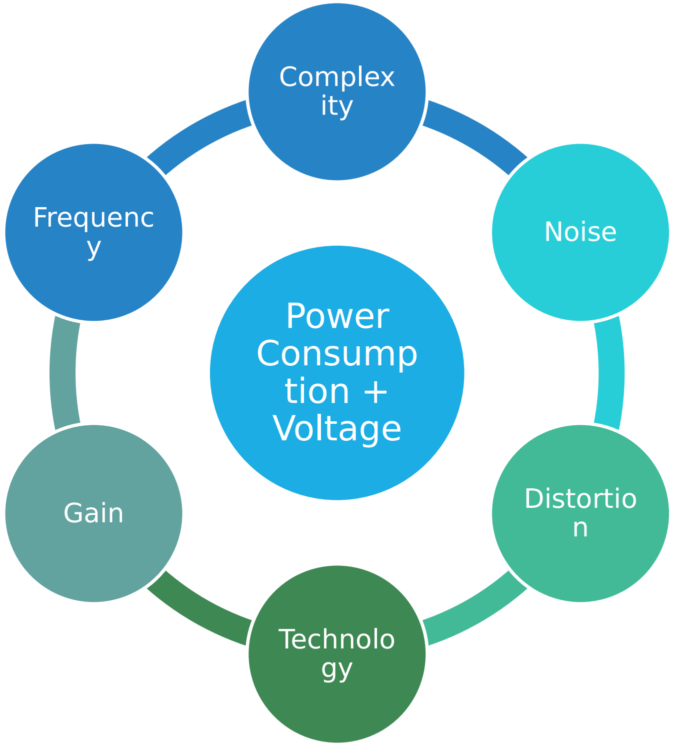
Agriculture passive sensors

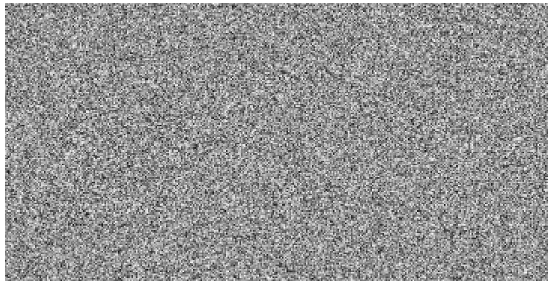

Smart Grids
Entertainment
Apps beyond imagination
5G
Security & surveillance
Smart parking
eHealth
Traffic priority
Connected house
Domotics
Traffic congestion
Smart Car
Car-to-car communication
Water leakages
Smart wearables
Water quality

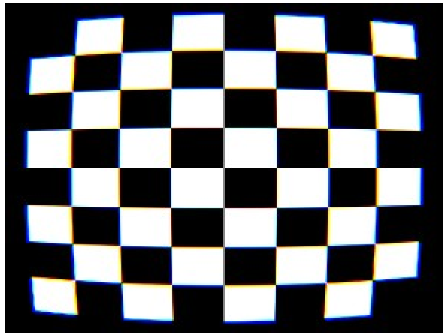
RADIO SYSTEM DRAWBACKS

Limitations

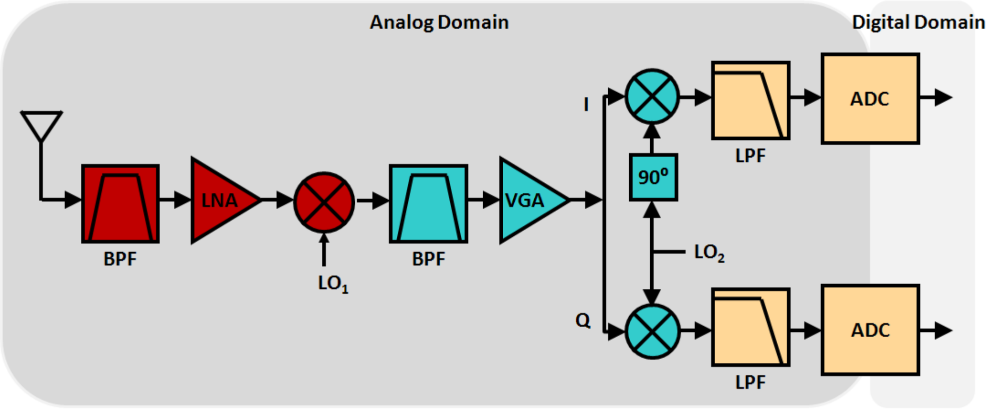








RF RECEIVERS

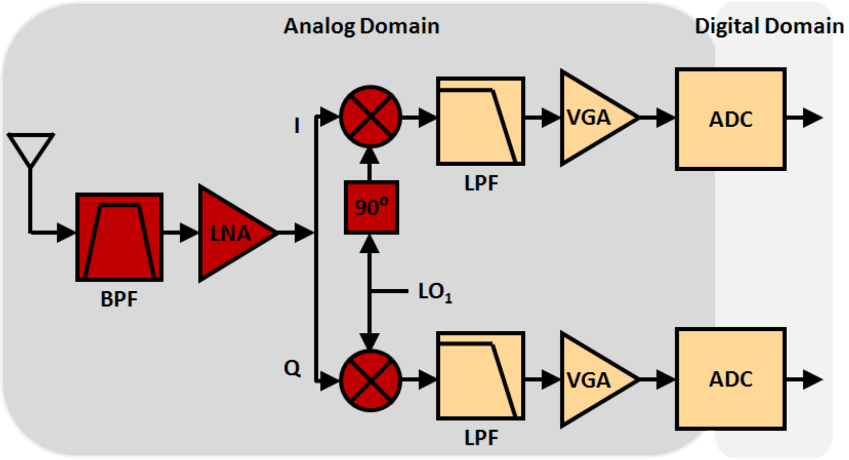


Super-heterodyne

- Conversion to the digital domain at baseband where it can be processed
- Currently adopted in most radio receivers due to low cost components
- Full on-chip integration is concerned and its design to a specific channel → prevents the expansion of receiving band

Zero-IF

- Signal is selected at RF by BPF, amplified and directly translated to DC
- Evident reduction in number of components → high level integration
- Components much more difficult to design DC offset, 2nd order IMD products generated around DC



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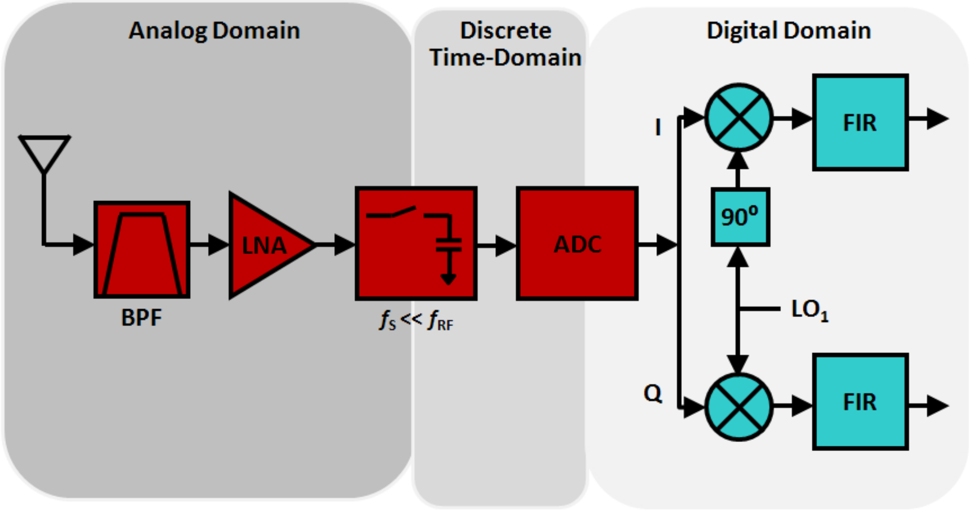
SOFTWARE DEFINED RADIO

Bandpass Sampling Receiver:

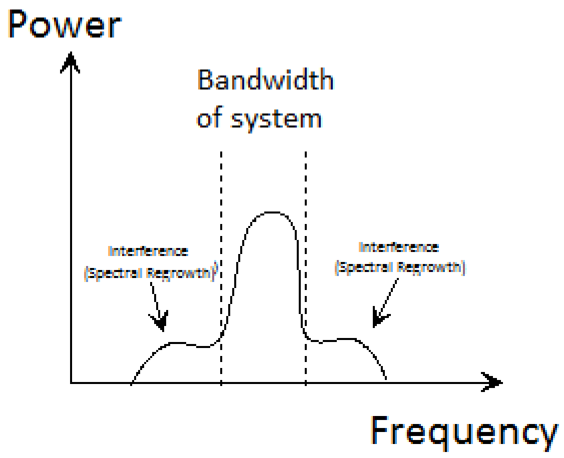


- Takes the fact that S/H circuit translates the signal to 1st Nyquist zone
- Digital processing capabilities exploited → multi-band reception
- Mandatory BPF to avoid overlap of signals → tunable or bank of filters
  - Analog BW of ADC must include RF carrier

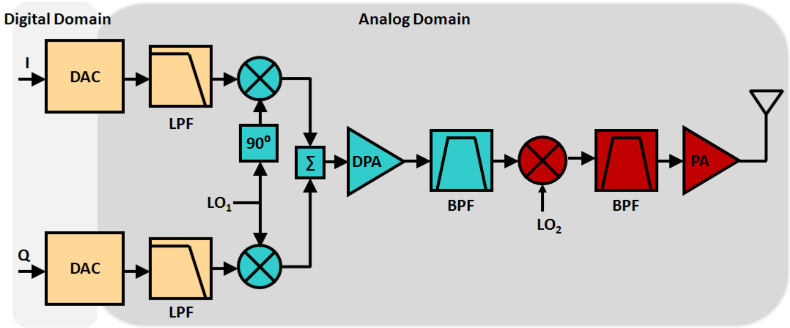
TRANSMITTER

The RF transmitter should also fulfill some requests, for instance:

- Use only the bandwidth that refers to the system standards
- Create low values of harmonic distortion
- Transmit the maximum RF power and simultaneously consume the minimum DC power from the system



TRANSMITTER

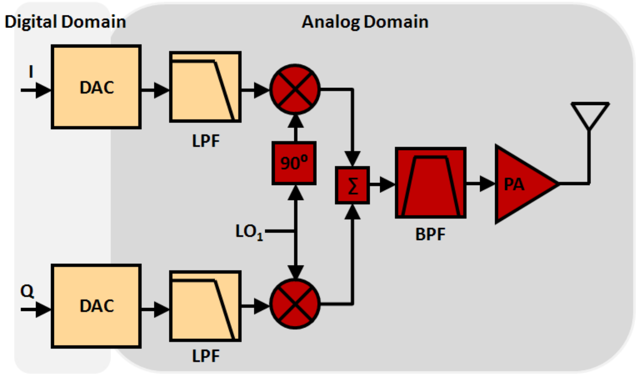


Super-Heterodyne Transmitter

- Signal created in digital domain, modulated at IF, and up-converted
- I/Q modulator working at IF; Output spectrum is far away from LO
- Suffers from similar problems of the receiver case
- Multi-mode implementation is difficult

Direct-Conversion Transmitter

- Digital baseband signals are converted and directly modulated to RF
- Reduced amount of circuitry that allows high level integration
- Carrier leakage, phase gain mismatch, and requires highly linear PA
- With careful design can be employed in SDR TX's

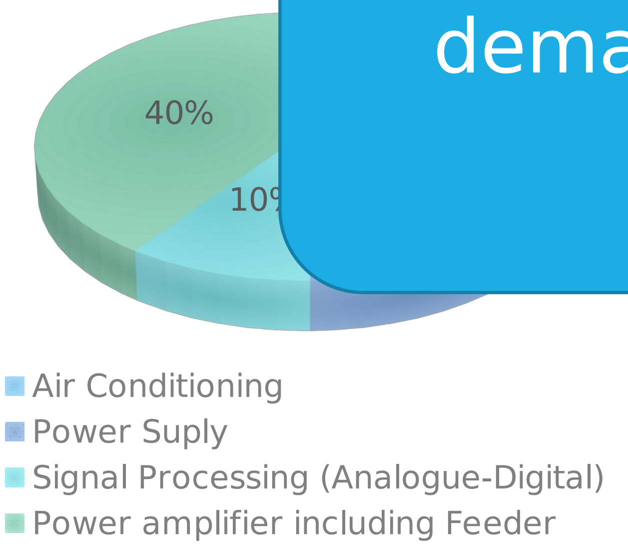


Mobile gadgets

If 10% of the world's mobile phone users turned off their chargers after use, the energy saved in one year could power 60,000 European homes.

MOTIVATION ENERGY WASTE IN NETWORKS

Base Consu



5G Communications will have a demand of extra 300% Energy compared with 4G

Huawei White Paper

Network

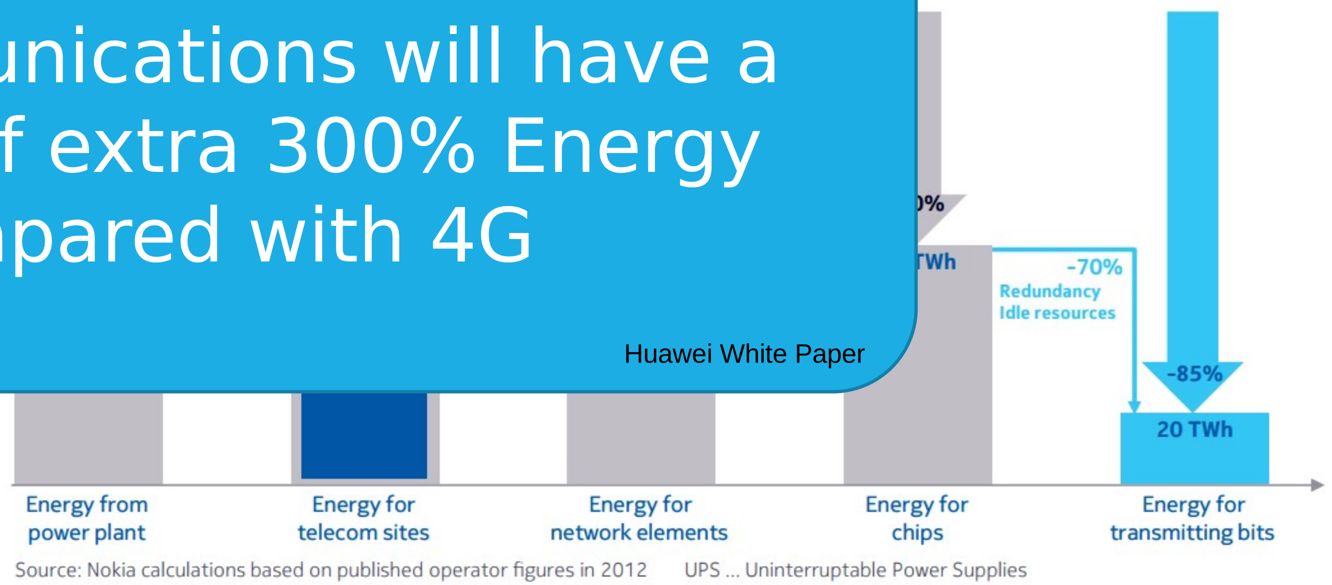


Figure 2: Where energy is consumed in a network - only 15% are used to "transmit bits"

Source: 2010 data

http://www.gsma.com/mobilefordevelopment/

RADIO COMMUNICATIONS

These radio architectures are responsible for a large amount of energy consumption….

MOTIVATION ENERGY W

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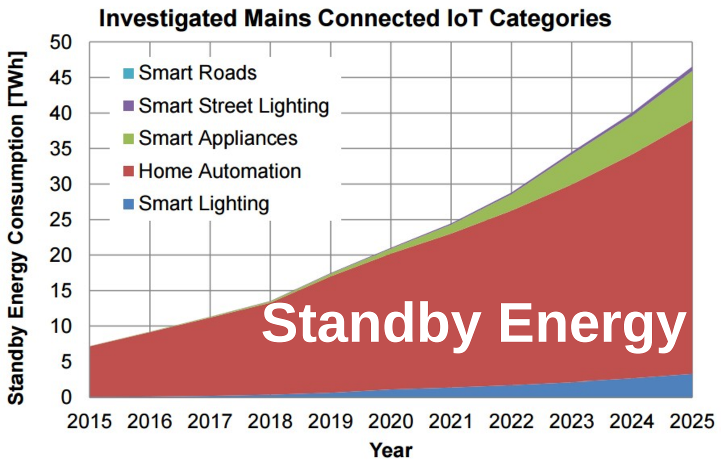
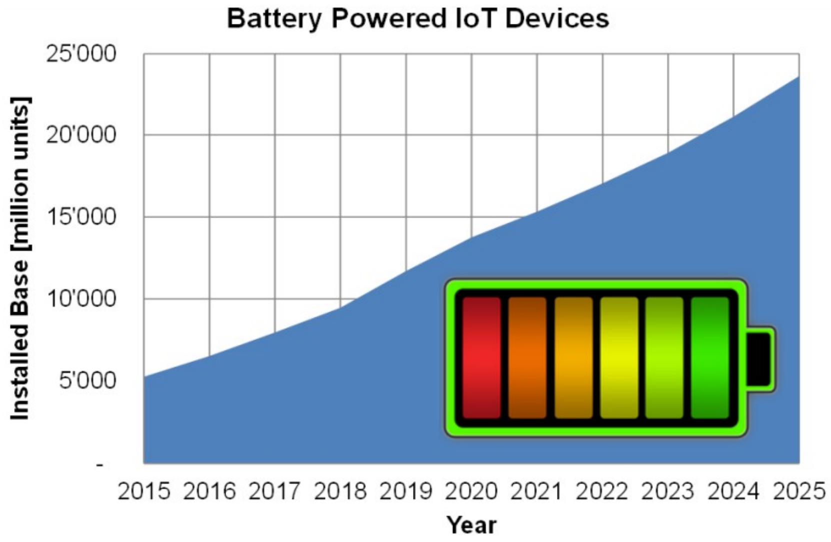
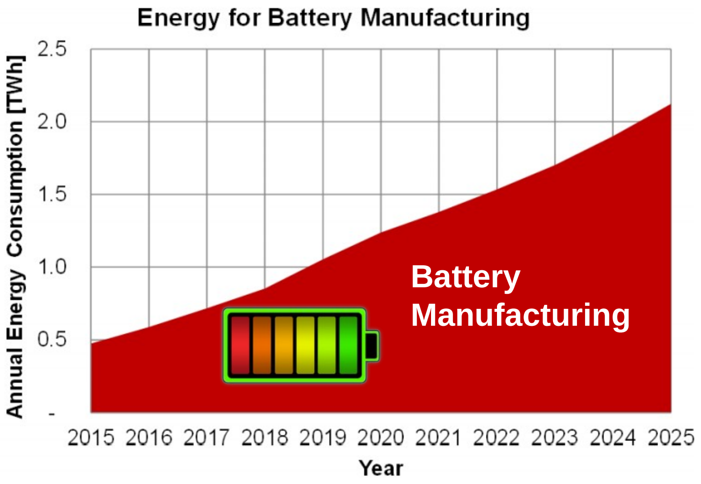


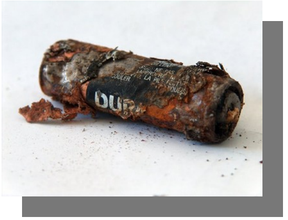




Source: 2016 data http://edna.iea-4e.org

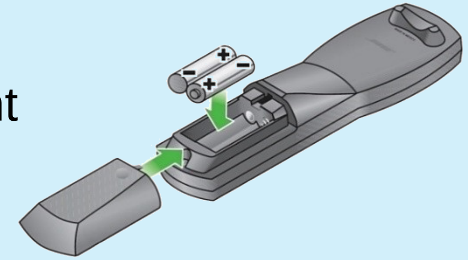
BATTERIES

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



Case study

- 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 !!

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ENERGY CONSUMPTION

APPROACHES SOLUTIONS FOR LOW BIT RATE

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How much power is low power?

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MARKET SOLUTIONS POWER CONSUMPTION

Typical example from one of the top sellers of IoT Sensors

Parameter	Value	Unit
Minimum supply voltage	1.9	V
Temperature range	-40 to +85	°C
Supply current in transmit @ -10dBm output power	9	mA
Supply current in receive mode	12.5	mA
Supply current for µ-controller 4MHz @ 3volt	1	mA
Supply current for ADC	0.9	mA
Maximum transmit output power	10	dBm
Data rate	50	kbps
Sensitivity	-100	dBm
Supply current in power down mode	2.5	µA

SoC 1 - Sub <1GHz

- 2.4 GHz transceiver
  - -96 dBm sensitivity in *Bluetooth*® low energy mode
  - 1 Mbps, 2 Mbps supported data rates
  - TX power -20 to +4 dBm in 4 dB steps
  - Single-pin antenna interface
  - 5.3 mA peak current in TX (0 dBm)
  - 5.4 mA peak current in RX
  - RSSI (1 dB resolution)

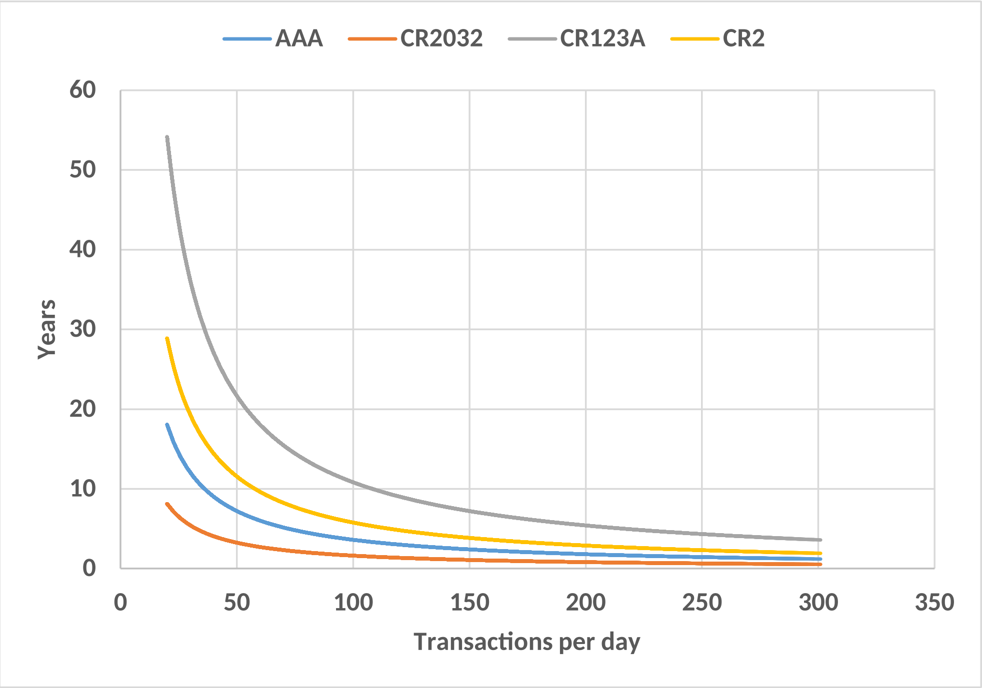
SoC 2 – UltraLow Power Bluetooth

Transmit – 17mW
Receive – 24mW

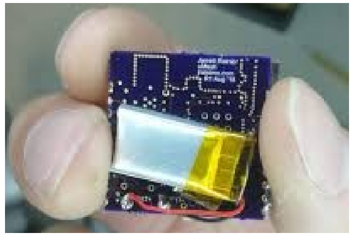
Supply Voltage 1,7 to
3,6 V
Transmit/Receive –

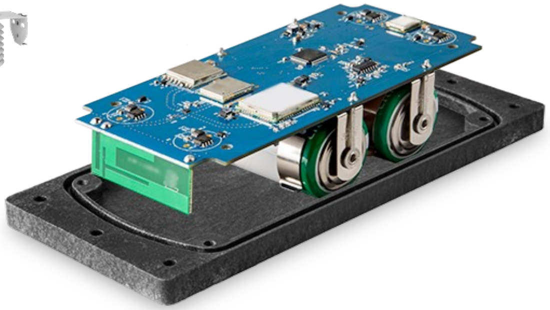
MARKET SOLUTION

CONSUMPTION



Type	AAA	CR2032	CR123A	CR2
Material	Alkaline	LiMn02*	Lithium	Lithium
Voltage	3V	3V	3V	3V
Capacity	500 mAh	225 mAh	1500 mAh	800 mAh





"Guilty as charged."

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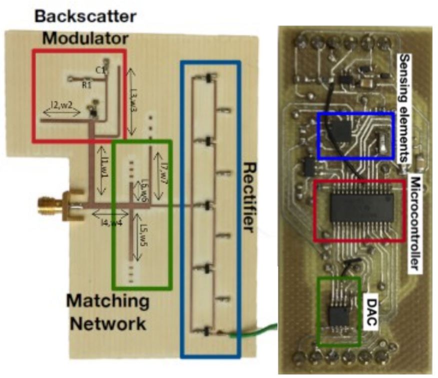
THE SOLUTION

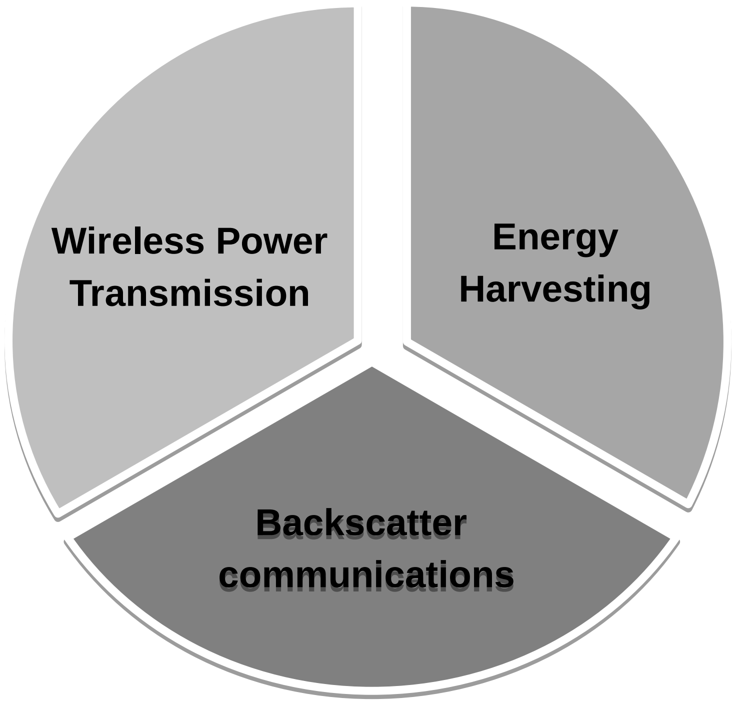
LoRa – 60 mW to 400 mW

Bluetooth – 5 mW to 90 mW

WiFi – 50 mW to 1 W



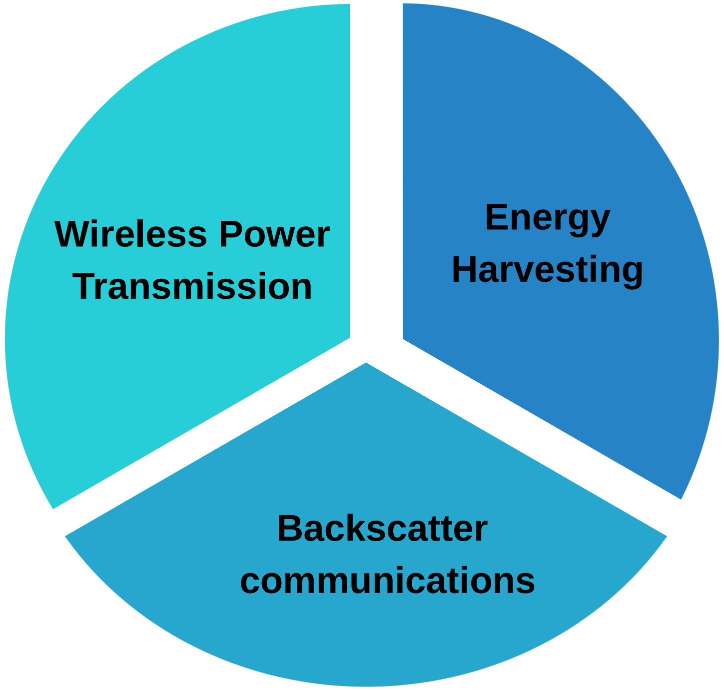
Passive

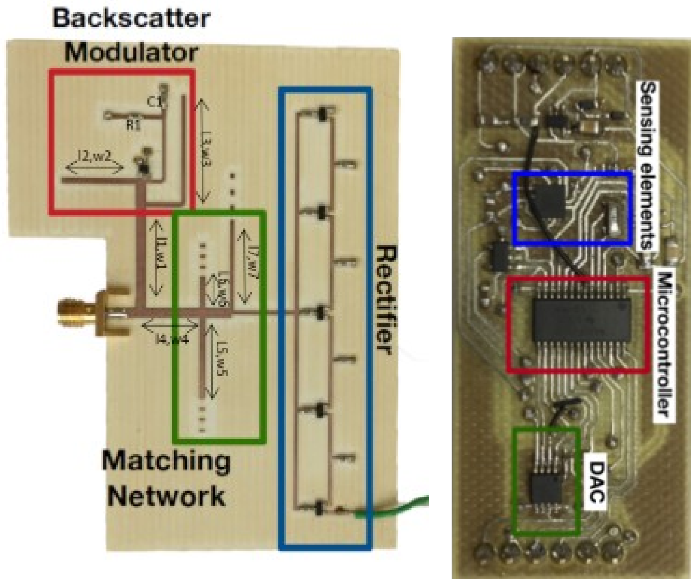


- **Remove the need of power for transmit / receive!**
- **Eliminate batteries!**

SWIPT

Simultaneous Wireless Information and Power Transfer





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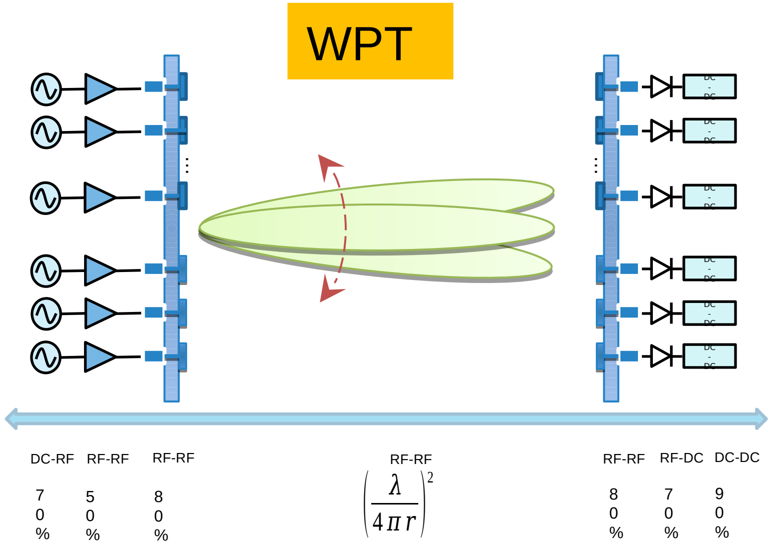
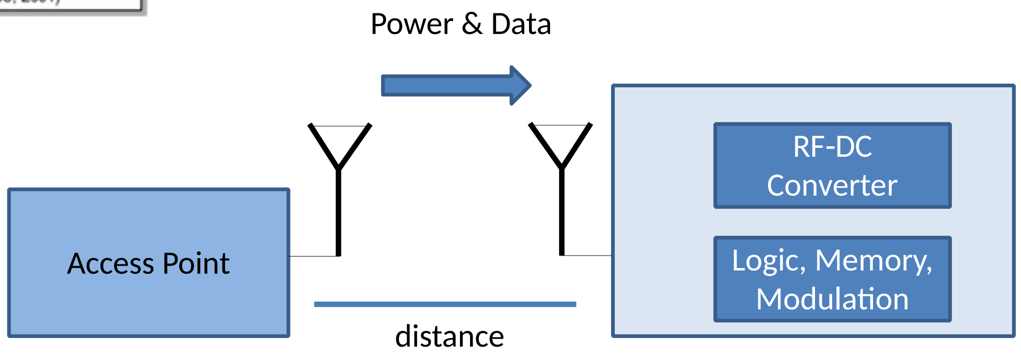
ENERGY HARVESTING VS WIRELESS POWER TRANSMISSION

Energy Source	Power Density & Performance		Source of Information
Acoustic Noise	0.003 0.96	μW/cm3 @ 75Db μW/cm3 @ 100Db	(Rabaey, Ammer, Da Silva Jr, Patel, & Roundy, 2000)
Temperature Variation	10	μW/cm3	(Roundy, Steingart, Fréchette,Wright, Rabaey, 2004)
Ambient RF	1	μW/cm2	(Yeatman, 2004)
Ambient Light	100 100	mW/cm2 (direct sun) _W/cm2 (illluminated office)	Not Cited
Thermoelectric	60	_W/cm2	(Stevens, 1999)
Vibration (micro generator)	4 800	_W/cm3 (human motion - Hz) _W/cm3 (machines – kHz)	(Mitcheson, Green, Yeatman, & Holmes, 2004)
Vibrations (Piezoelectric)	200	μW/cm3	(Roundy, Wright, & Pister, 2002)
Airflow	1	μW/cm2	(Holmes, 2004)
Push Buttons	50	_J/N	(Paradiso & Feldmeier, 2001)
Shoe Inserts	330	μW/cm2	(Shenck & Paradiso, 2001)
Hand Generators	30	W/kg	(Starner & Paradiso, 2004)
Heel Strike	7	W/cm2	(Yaglioglu, 2002) (Shenck & Paradiso, 2001)

Comparison of Power Density of Energy Harvesting Methods





GSM/Cellular

Wi-Fi

Radio and TV broadcast

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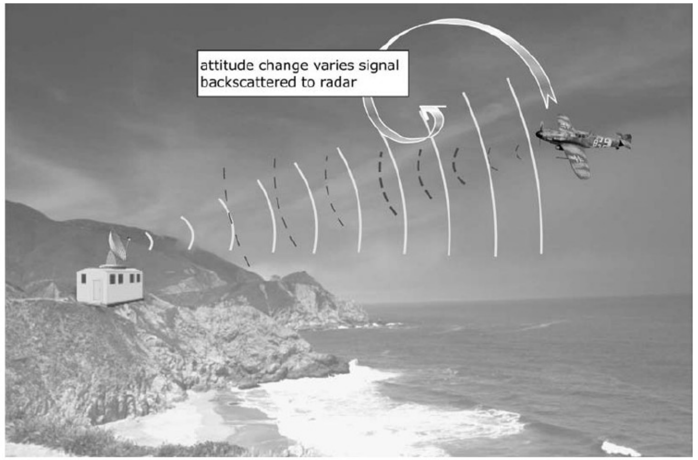
Source: The Journal of Technology Studies

BACKSCATTER COMMUNICATIONS

HISTORY OF BACKSCATTER RADIO

Backscatter RF tags have their origins in radar
- the origin of identification by power reflection

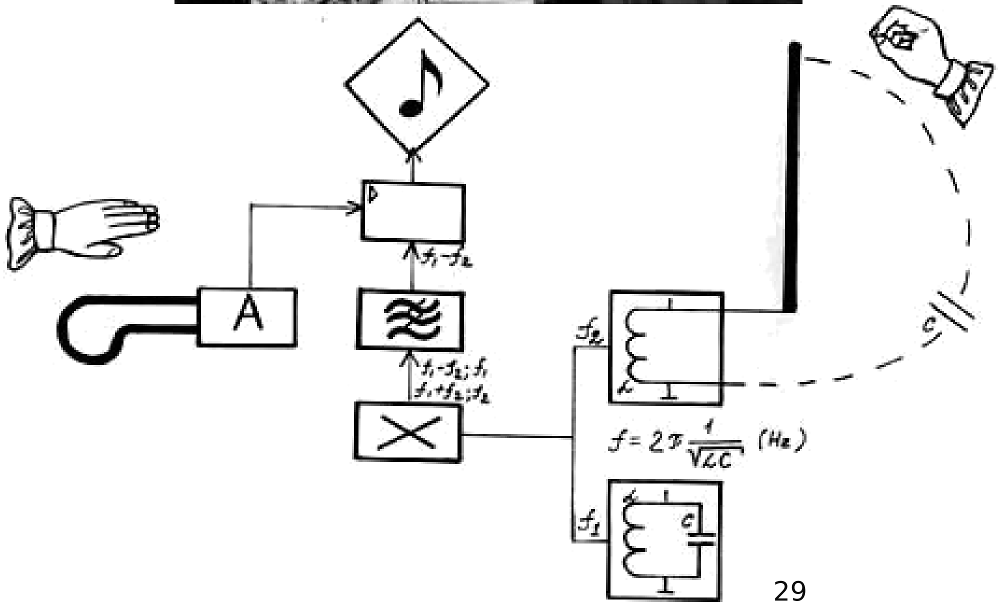


The IFF – Identification Friend or Foe system used during 2nd World War

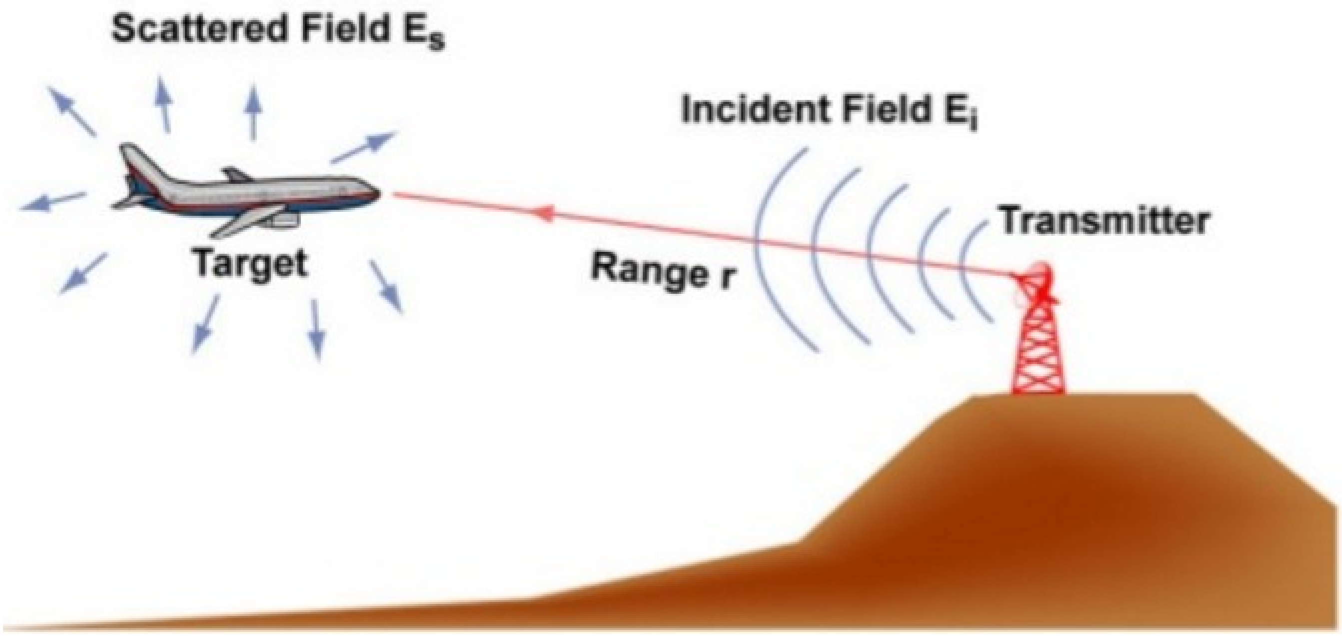
1940s . . . 2000s

- The foundation for RFID laid;
- Development of electronic article surveillance (EAS) systems (1-bit tags);
- RFID began finding mainstream commercial applications, in particular electronic toll collection. UHF and microwave tags still using discrete components.
- Development of useful Schottky diodes allow the entire tag to be integrated on a single chip.
- Establishment of widely accepted protocols – e.g. the Electronic Product Code protocols.

THEREMIN



RADAR CROSS SECTION



$$RCS = \lim_{r \to \infty} 4 \pi r^2 \frac{|E_s|^2}{|E_i|^2} \quad \text{(Unit: Area)}$$

Radar Cross Section (RCS) is the hypothetical area, that would intercept the incident power at the target, which if scattered isotropically, would produce the same echo power at the radar, as the actual target.

FAR FIELD OPERATION

Contrary to inductive coupling, electromagnetic backscatter operates in the far field.

The range can be calculated based on the energy available at the transponder which is calculated using the Friis formula:

$$P_T = A_{e2} \frac{P_{in}}{4\pi r^2} G_1 = \frac{\lambda^2}{4\pi} G_2 \frac{P_{in}}{4\pi r^2} G_1 \Leftrightarrow P_T = P_{in} \left(\frac{\lambda}{4\pi r} \right)^2 G_t G_r$$

Table 3.7 Free space path loss a_F at different frequencies and distances. The gain of the transponder's antenna was assumed to be 1.64 (dipole), the gain of the reader's antenna was assumed to be 1 (isotropic emitter)

Distance r	868 MHz	915 MHz	2.45 GHz
0.3 m	18.6 dB	19.0 dB	27.6 dB
1 m	29.0 dB	29.5 dB	38.0 dB
3 m	38.6 dB	39.0 dB	47.6 dB
10 m	49.0 dB	49.5 dB	58.0 dB

BACKSCATTER BATTERY-LESS PARADIGM

HISTORY OF BACKSCATTER RADIO

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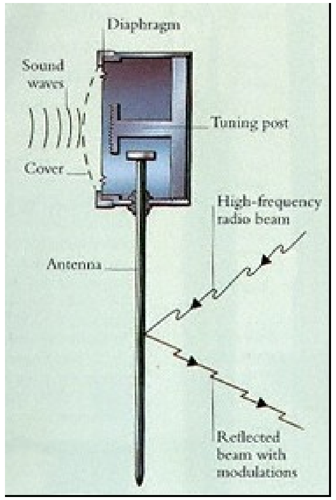
The Great Embassy Seal Bug

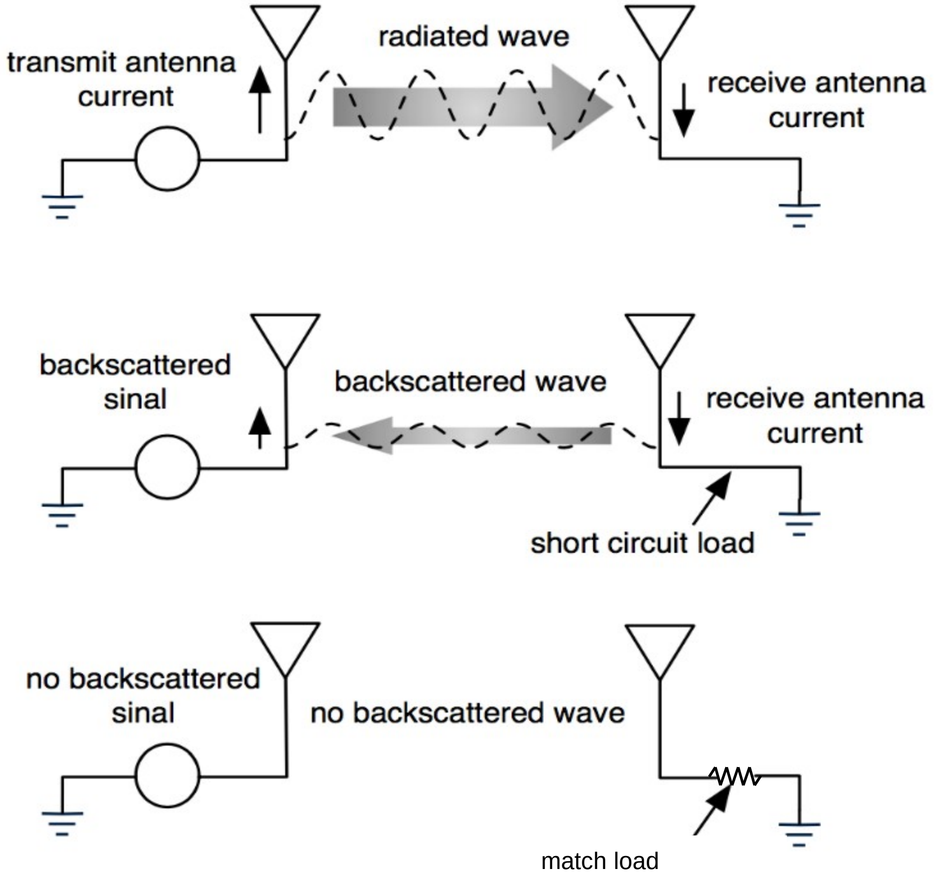
- Given as “gift” to US by USSR in 1946;
- Passive transduction of sound, interrogated from across the street in the Soviet Embassy;
- Undiscovered until 1952;

- Invented by Leon Theremin;
- Vibrating diaphragm changes capacitive load seen by antenna;
- Analog speech modulates the backscattered information;
- Reflected signal looks like small-carrier AM;



BACKSCATTER BATTERY-LESS PARADIGM

BACKSCATTER BATTERY-LESS PARADIGM



- Backscatter communications has its roots in radars type approach
- The RF-front end reflects part of an incoming electromagnetic wave back to the reader based on the information pattern
- The backscatter reflection efficiency is maximized for antennas that are resonating with the incoming signal frequency

BACKSCATTER

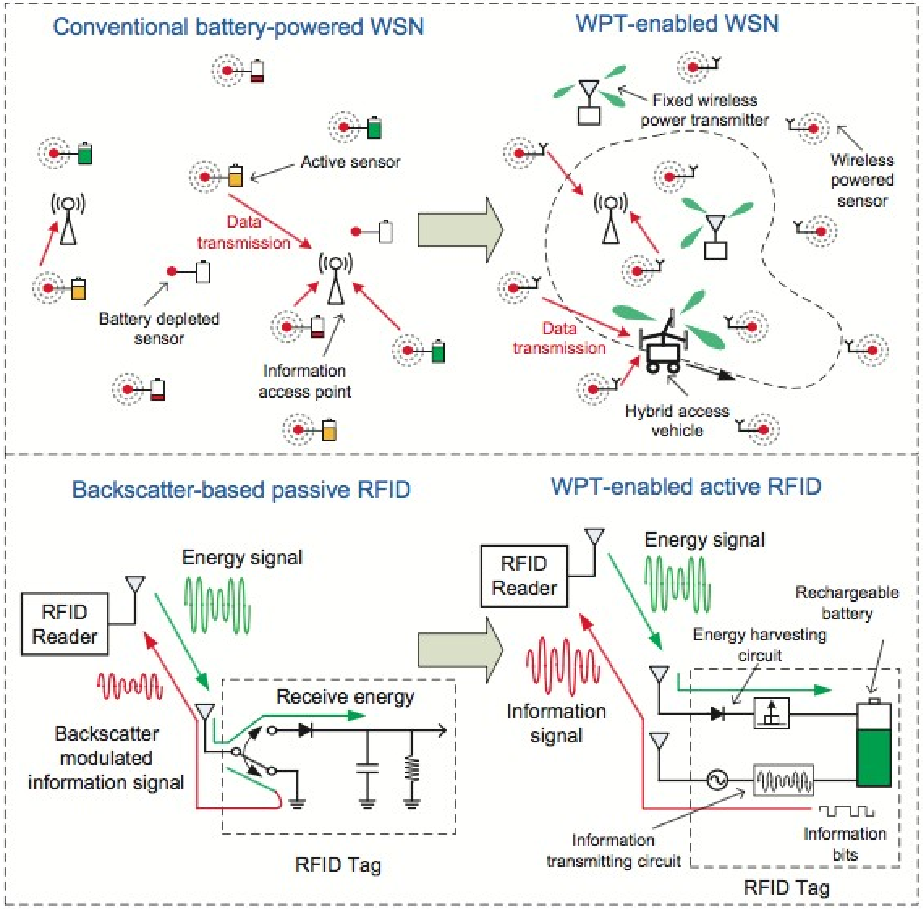
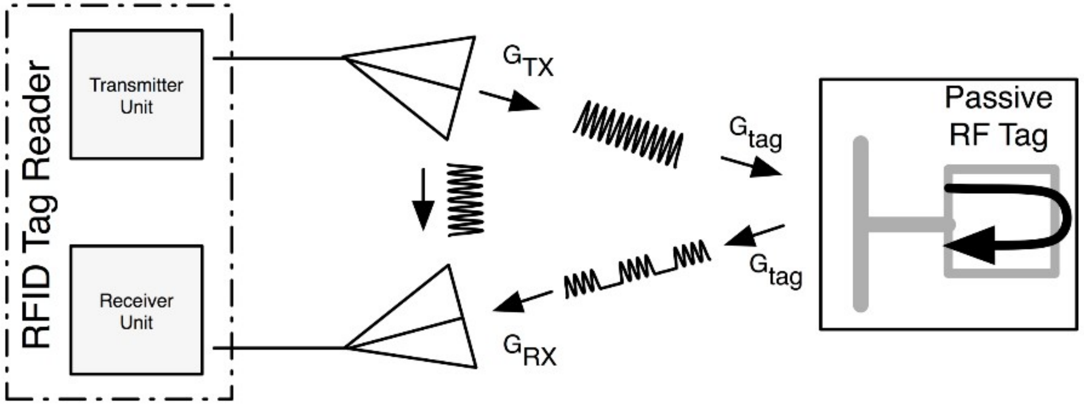


Figure taken from S. Bi, C. K. Ho, and R. Zhang, "Wireless powered Communication Networks: An Overview,"



RF tag communicates with a reader, by modulating the electromagnetic fields scattered from the RF tag's antenna.

Problems

- Limited range communication
- ASK or PSK modulation schemes (one bit of data per symbol)

Advantages

- No need of active components in wireless transceivers
- Low-power implementation

TRANSMIT AND RECEIVE SIGNALS

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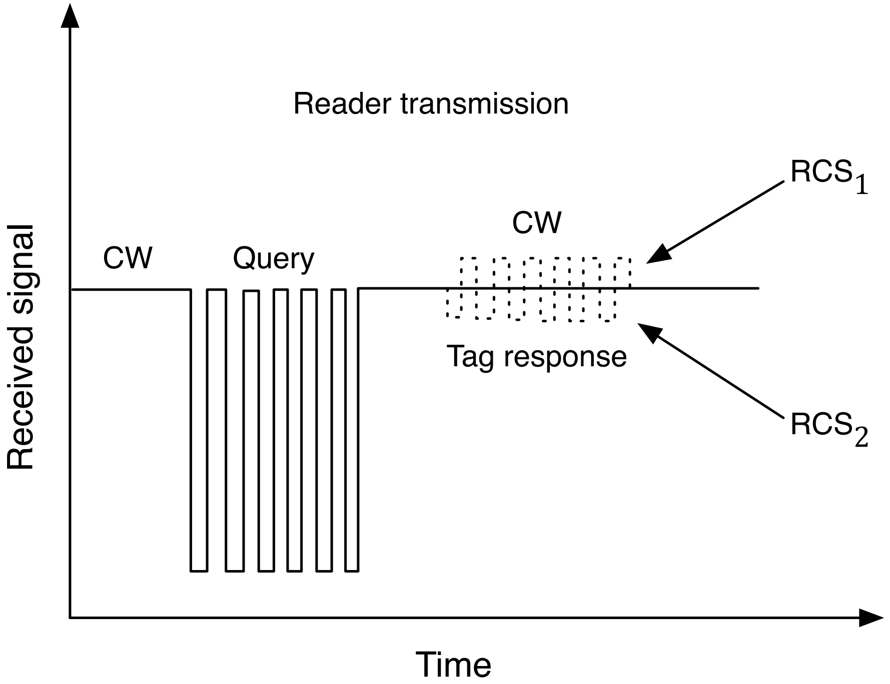
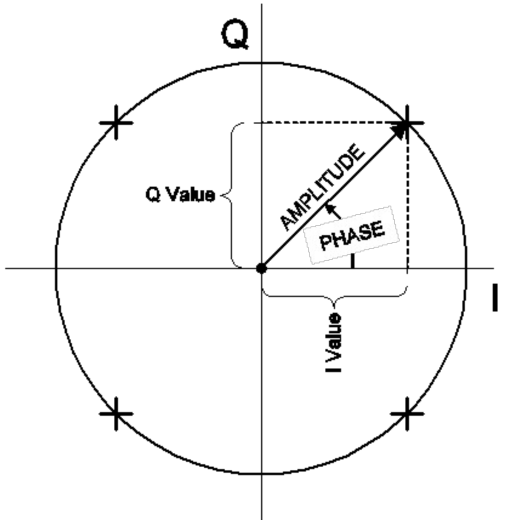
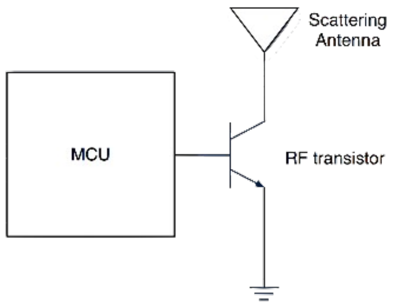


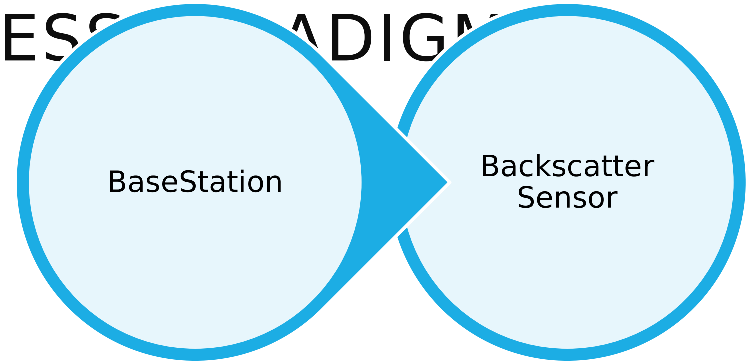
Signal transmitted on the forward link (reader to tag) contains both CW and modulated commands.

Each impedance state the tag presents a certain RCS high (RCS_1) and low (RCS_2) to provide significant difference in the backscattered signal.

BACKSCATTER BATTERY-LESS ... ADIGM

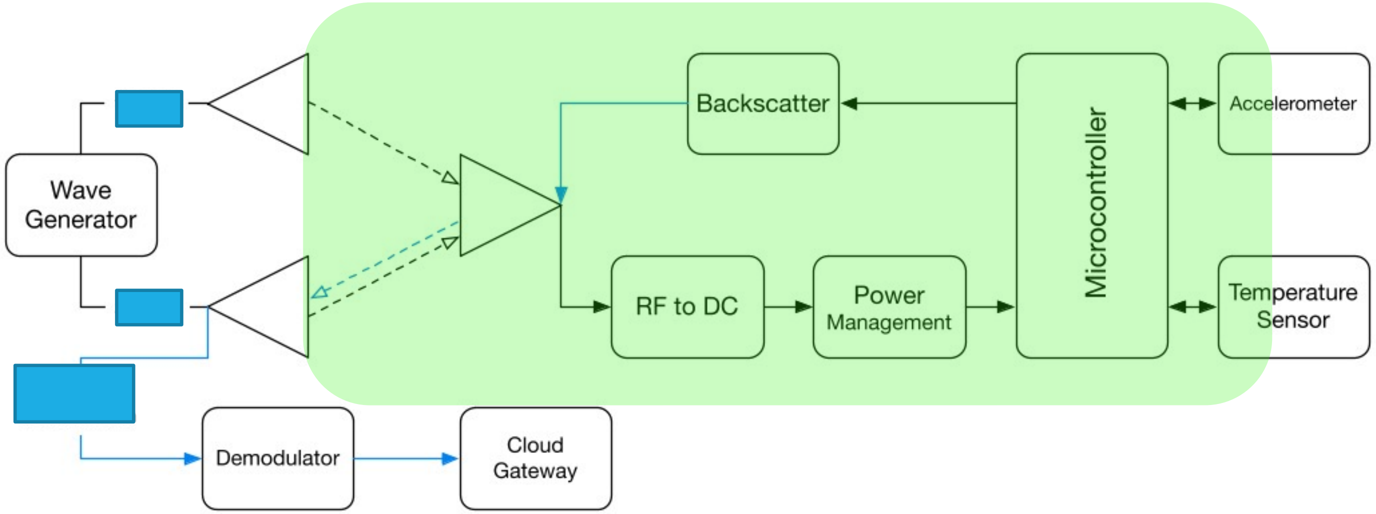




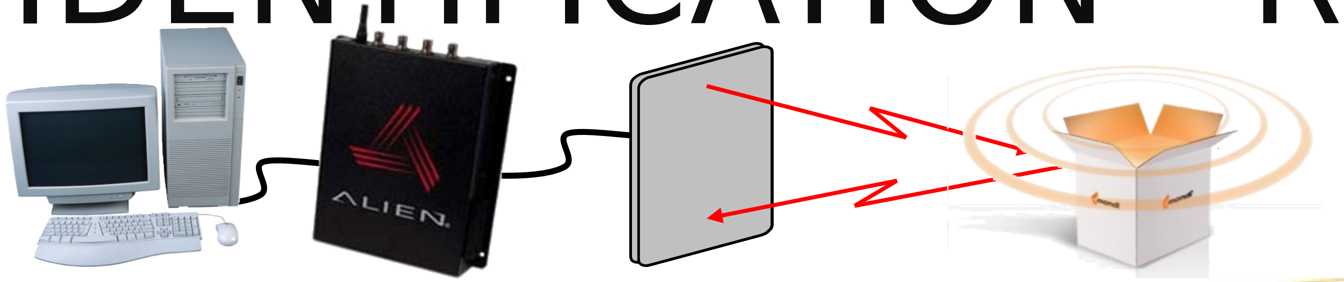


- RF Transmitter
- RF Receiver

- Voltage Harvester
- Signal Processor



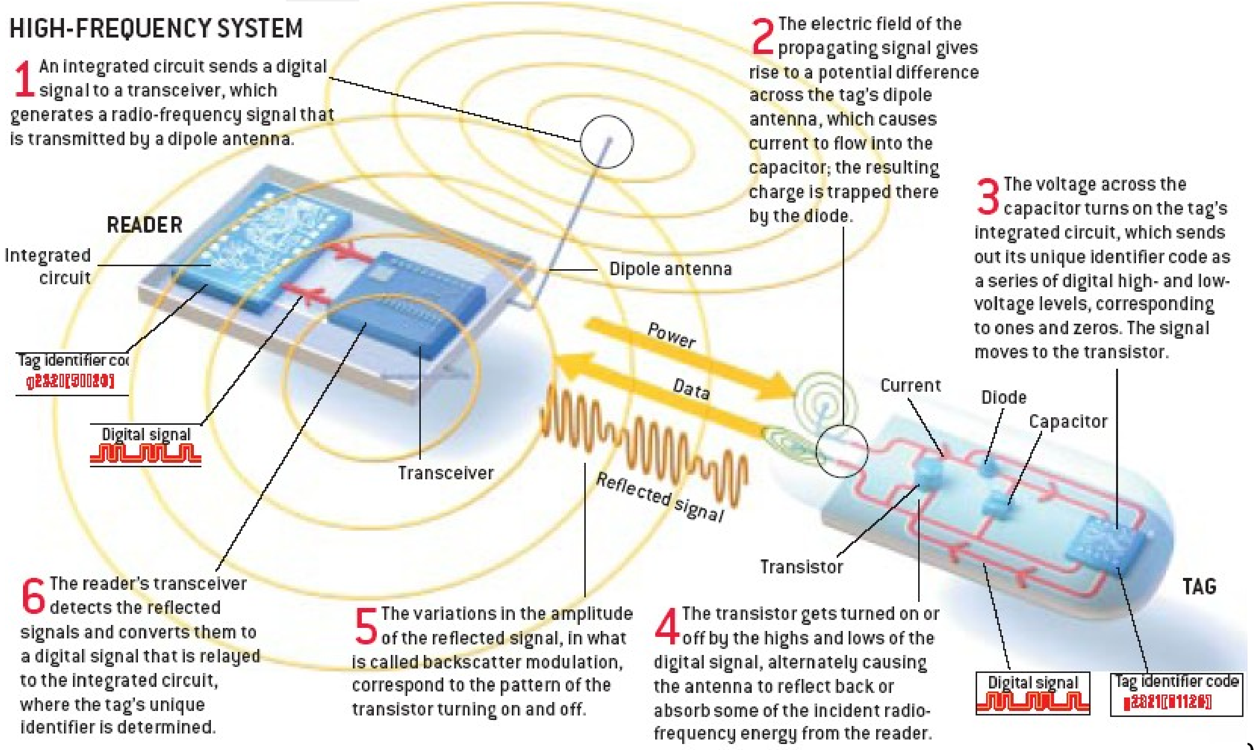
RADIO FREQUENCY IDENTIFICATION - RFID



Host

Reader module

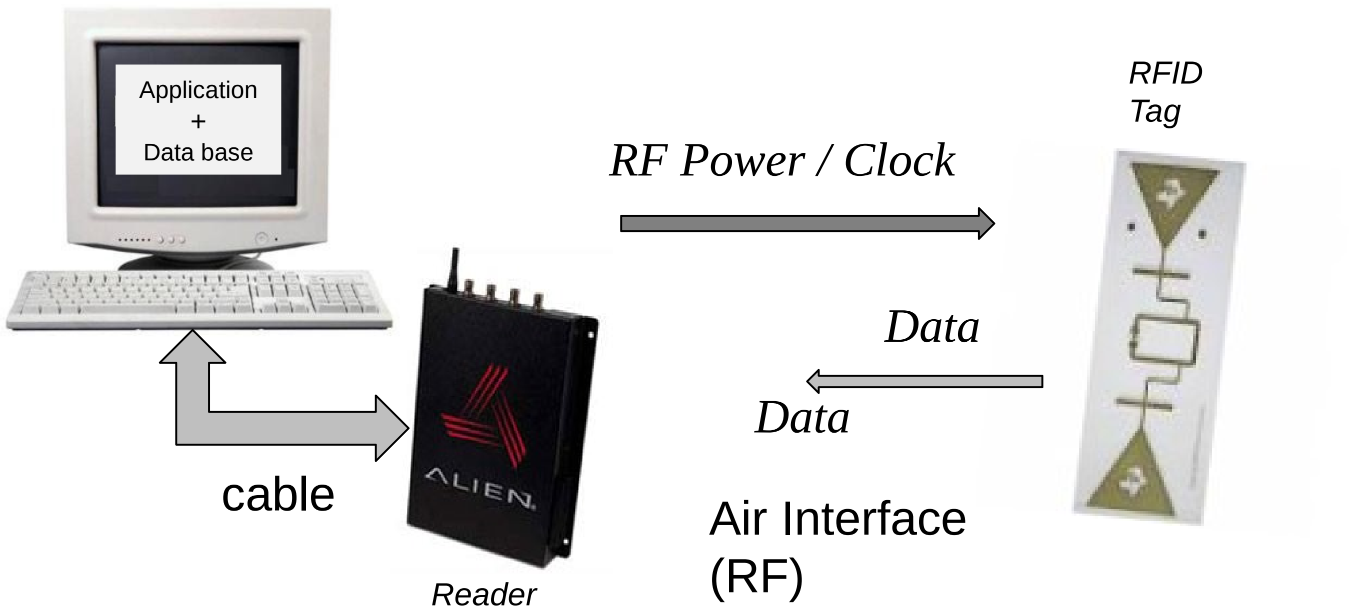
Antenna



PRINCIPLE OF OPERATION

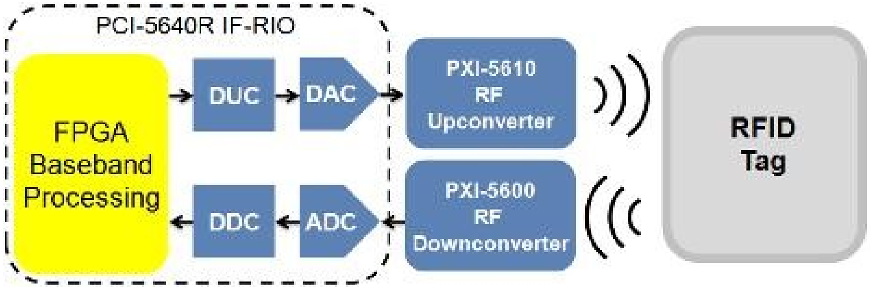
Basic components

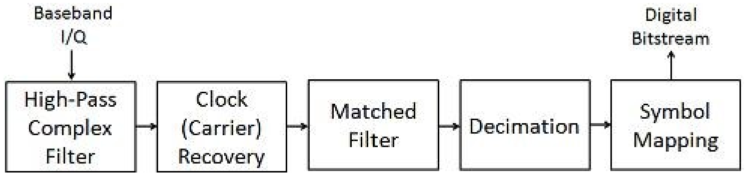
1) **Reader/Interrogator** – Used for read and store information in Tag
2) **Tag/Transponder** – small device which carries data (e.g. Tag ID)
3) **Host** - computer running user application



UHF RFID

Typical Readers are moving fast to a Software Defined Radio Solution, including a digital part and a RF up-converter and RF down-converter….





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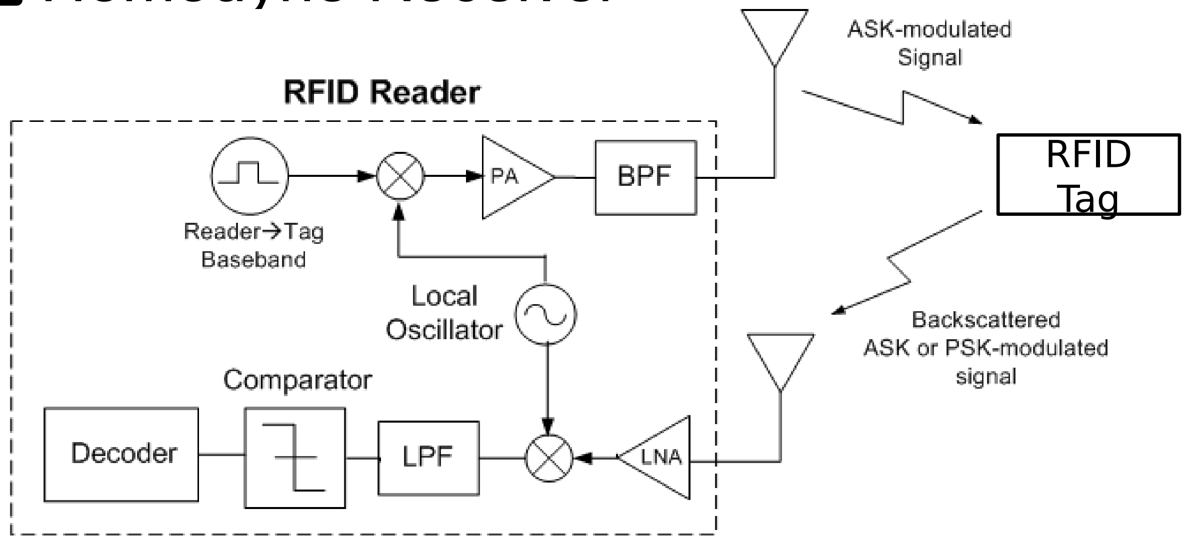
READER ARCHITECTURES

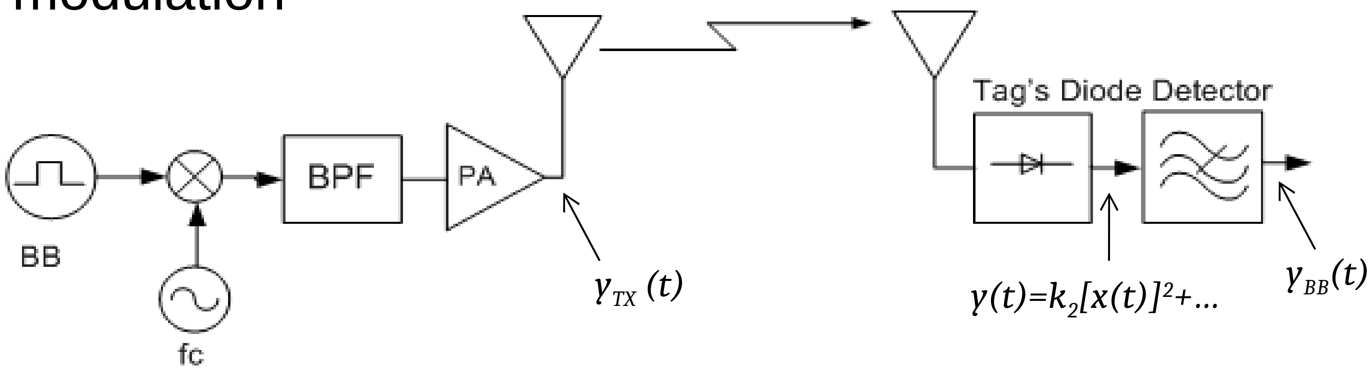
- ✓Transmitter ✉ ASK Modulator
- ✓Receiver ✉ Homodyne Receiver



DOWNLINK DATA COMMUNICATION

Downlink: Rader ✉ Tag communication

- ASK modulation



Baseband ASK signal: $m(t) = \sum_{k=-\infty}^{+\infty} a_k \delta(t - kT)$

Transmitted Signal: $y_{TX}(t) = m(t)\left\{A_C \frac{e^{j\omega_c t} + e^{-j\omega_c t}}{2}\right\}$

RF Carrier

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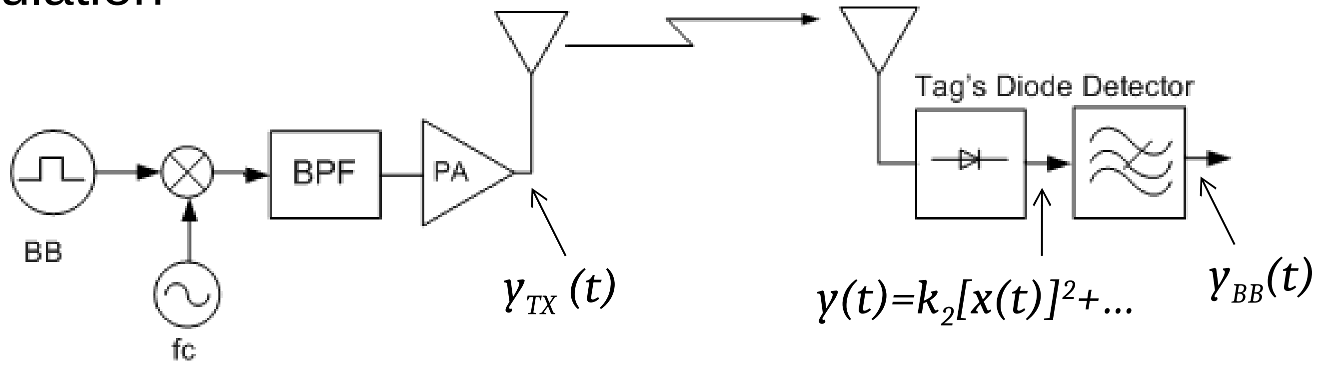
DOWNLINK DATA COMMUNICATION

Downlink: Rader ✉ Tag communication

- ASK modulation

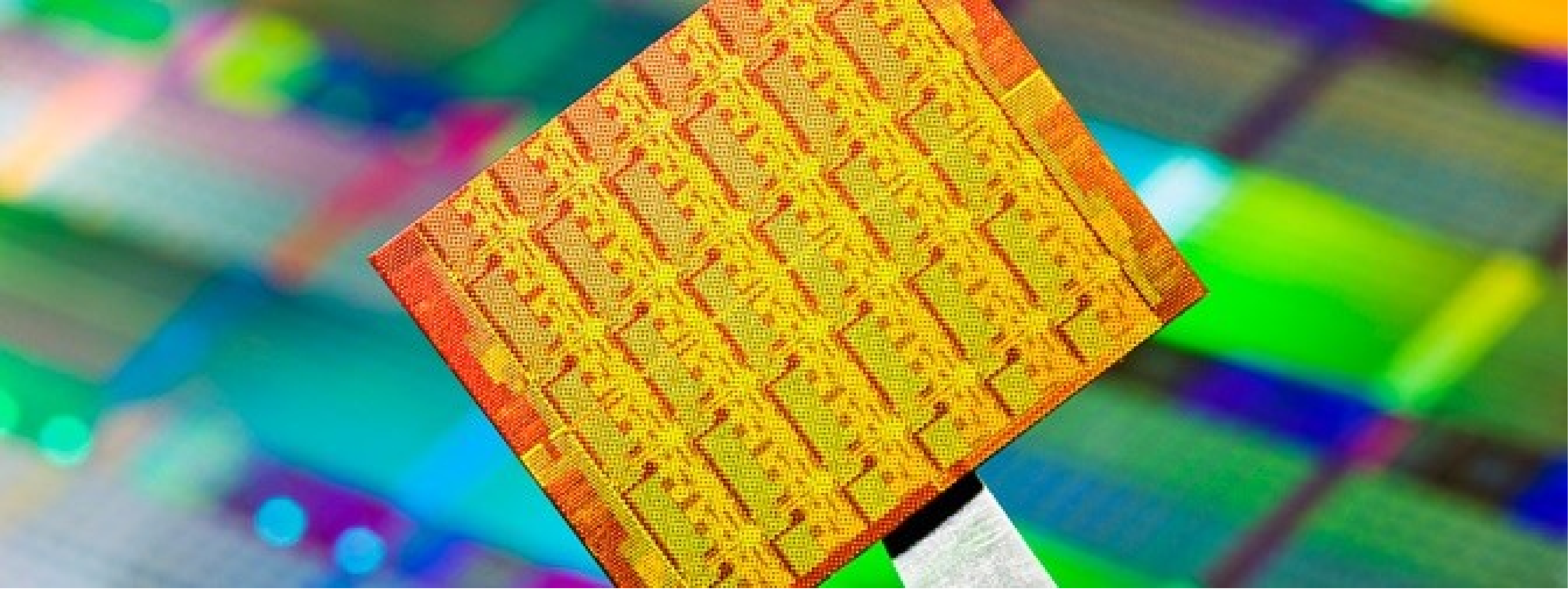


Envelope Demodulation:

$$y(t) = k_2\left[m(t)\left\{A_c\,\frac{e^{j\omega_c t}+e^{-j\omega_c t}}{2}\right\}\right]^2$$

After low-pass filtering, the baseband signal sent by the reader is recovered by the Tag:

$$y_{BB}(t) = \frac{A_c^2 k_2}{2}\,[m(t)]^2$$



HOW TO DESIGN A MICROWAVE BACKSCATTER TAG

BACKSCATTER - STEPS FOR IMPLEMENTATION

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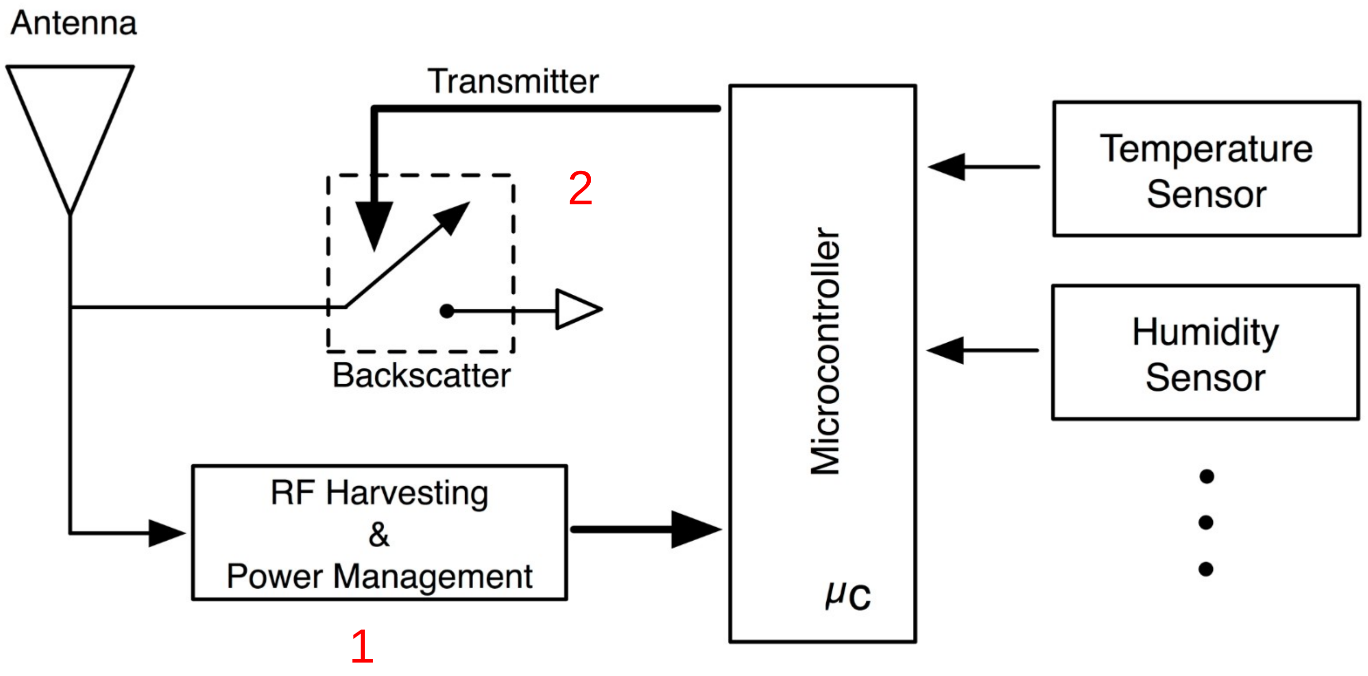
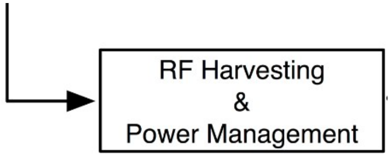
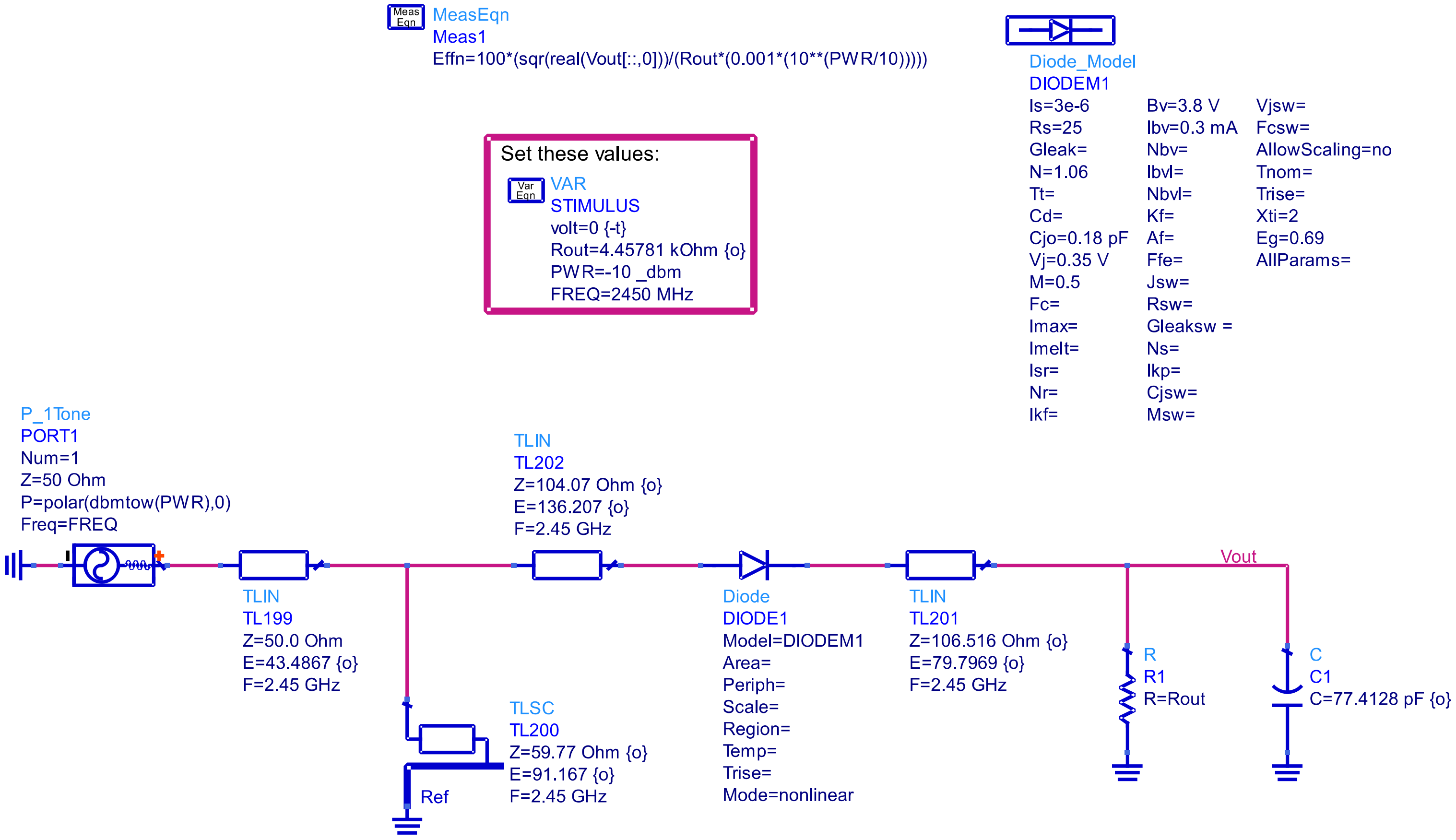


Backscatter design:

- Choose the frequency for the circuit; 2.45 GHz
- Design the rectifier for the chosen frequency and optimize it for the highest efficiency! 1
- Design the backscatter modulator; 2
- Combine both solutions (Rectifier + Backscatter modulator).



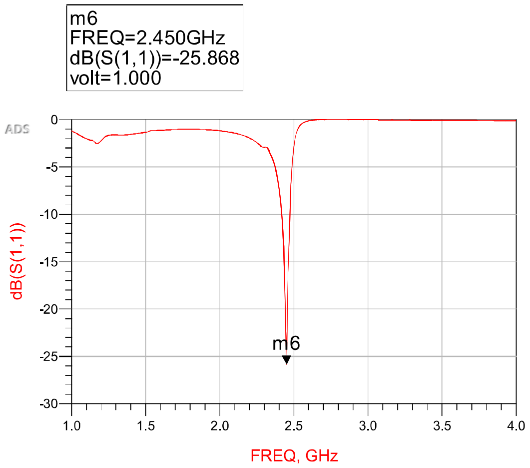
DESIGN THE RF-DC FOR 2.45 GHZ

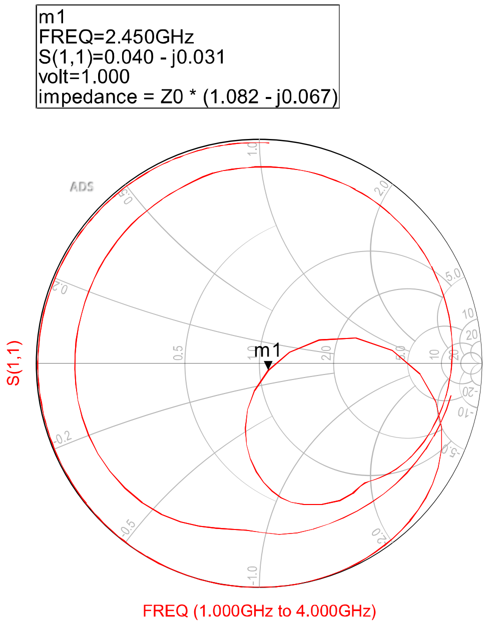


RESULTS OF RF-DC

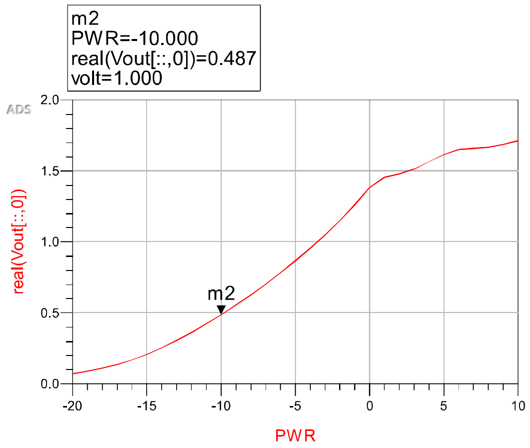
Using large signal S-parameters

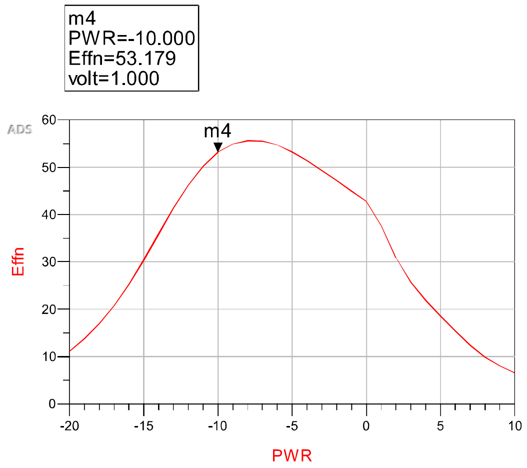
Matching Frequency = 2.45 GHz



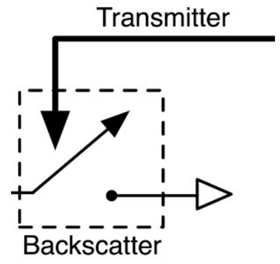


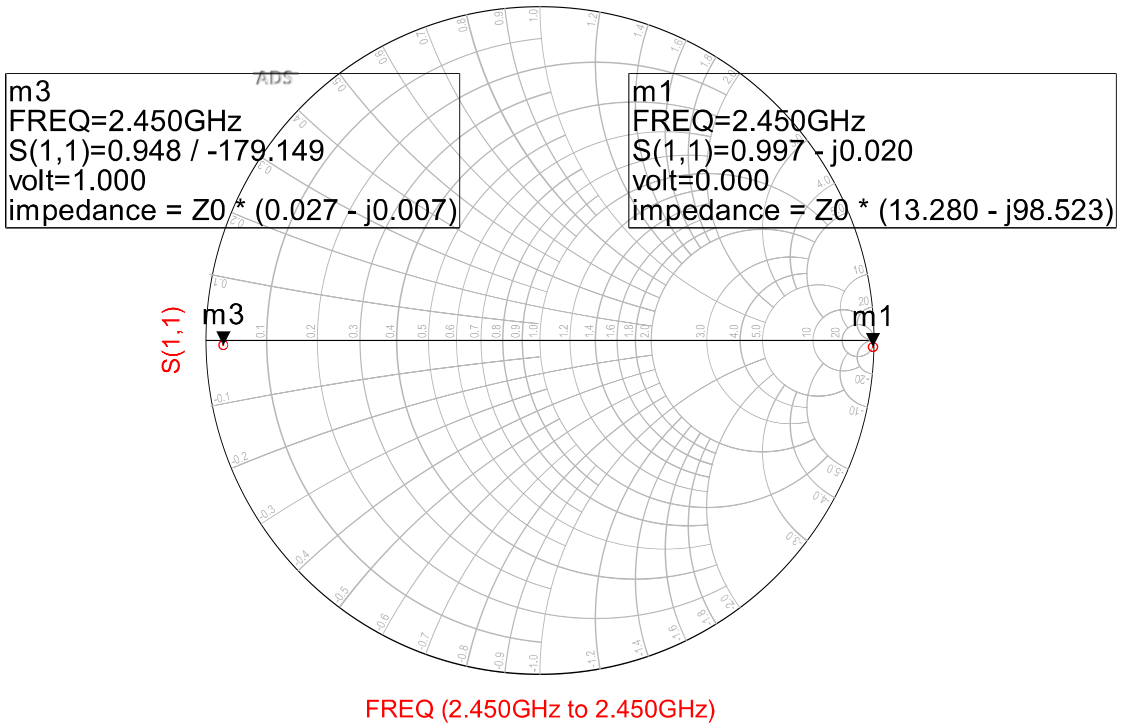
For -10 dBm (0.1 mW) of input power the output voltage generated is 0.487 V with 53.2 % of efficiency

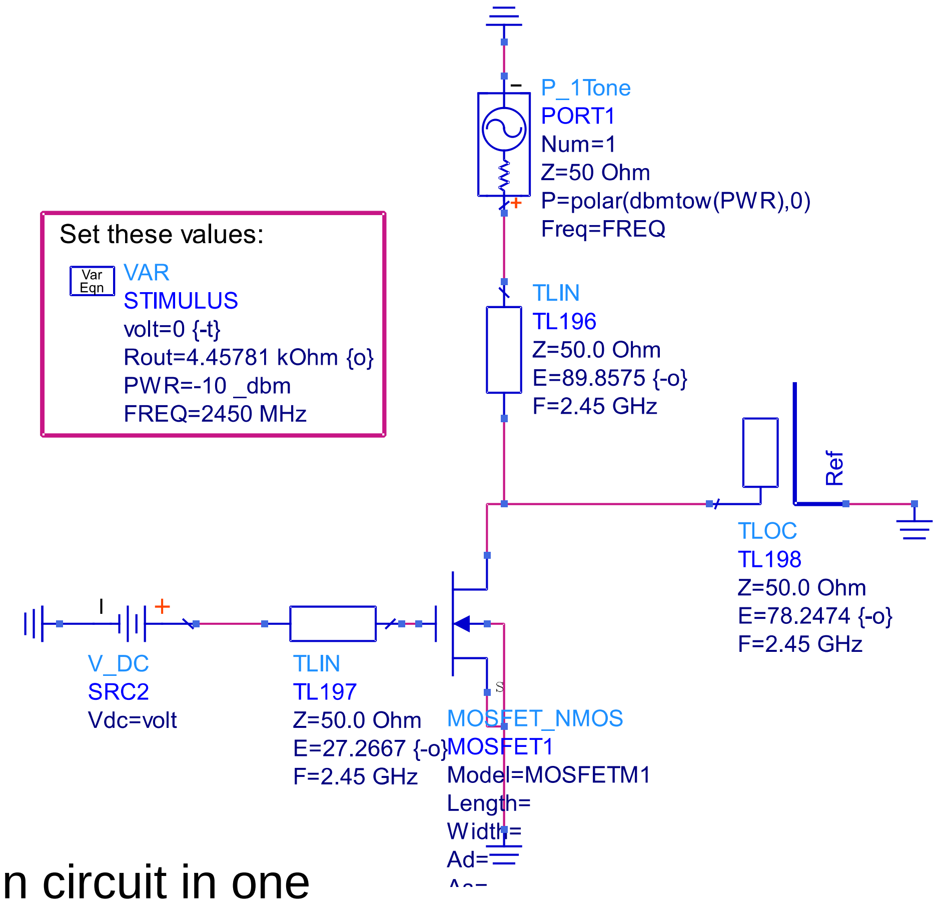




DESIGN OF BACKSCATTER MODULATOR







The goal is to optimize the modulator to behave as an open circuit in one state of transistor (0 V) and as a short circuit in other state (1 V).

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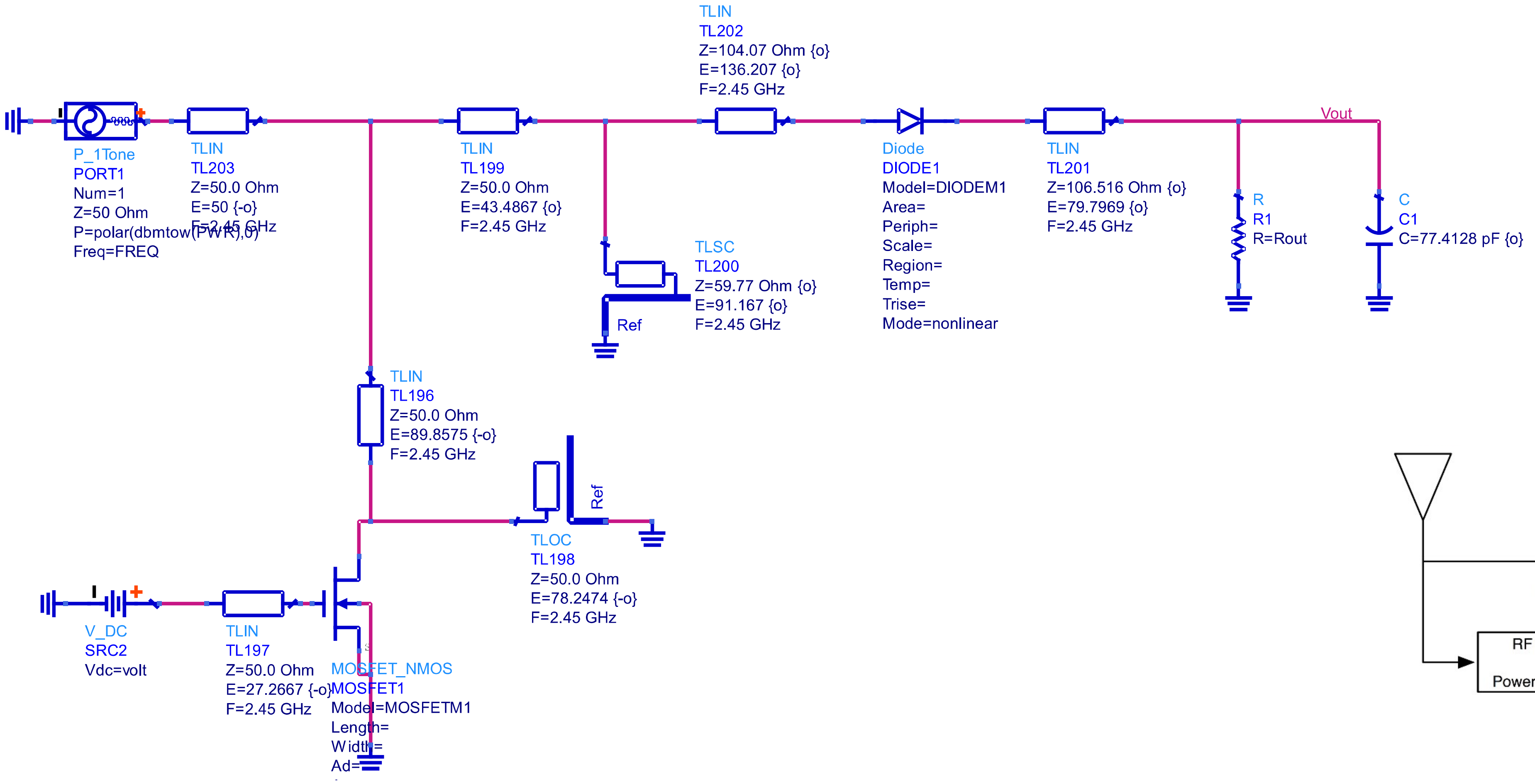
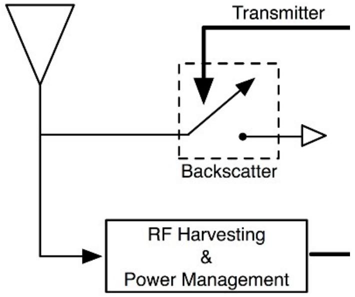
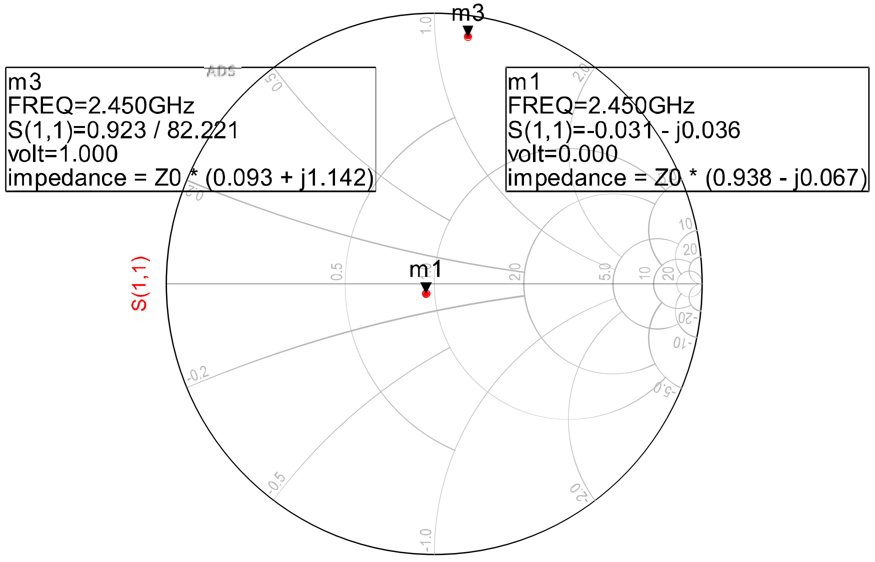
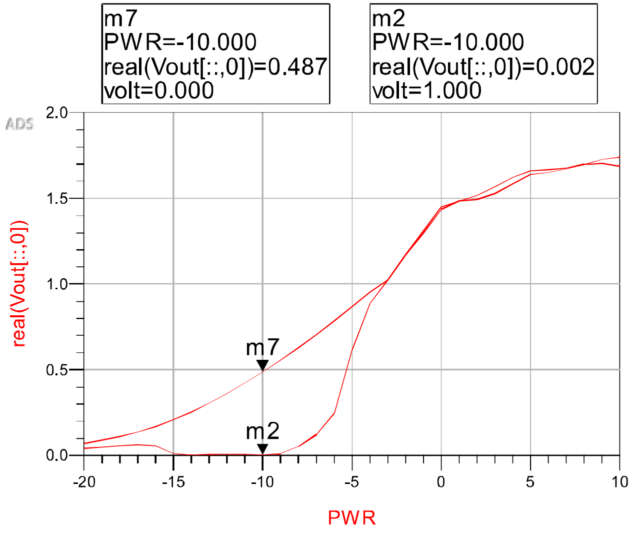
COMBINING SOLUTIONS – BACKSCATTER DESIGN

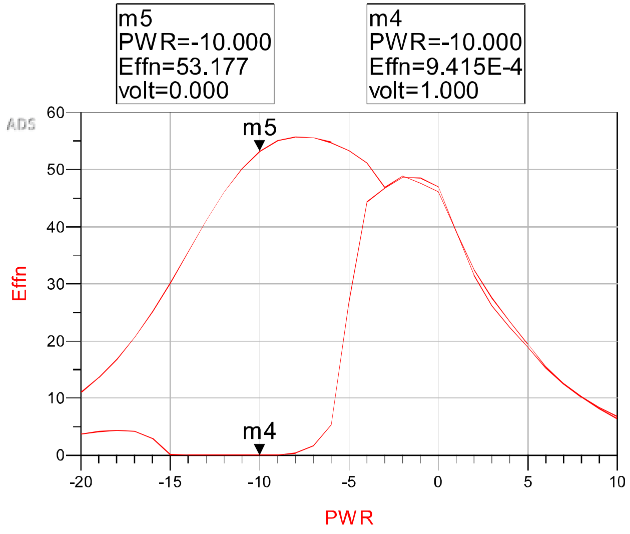




RESULTS OF BACKSCATTER CIRCUIT



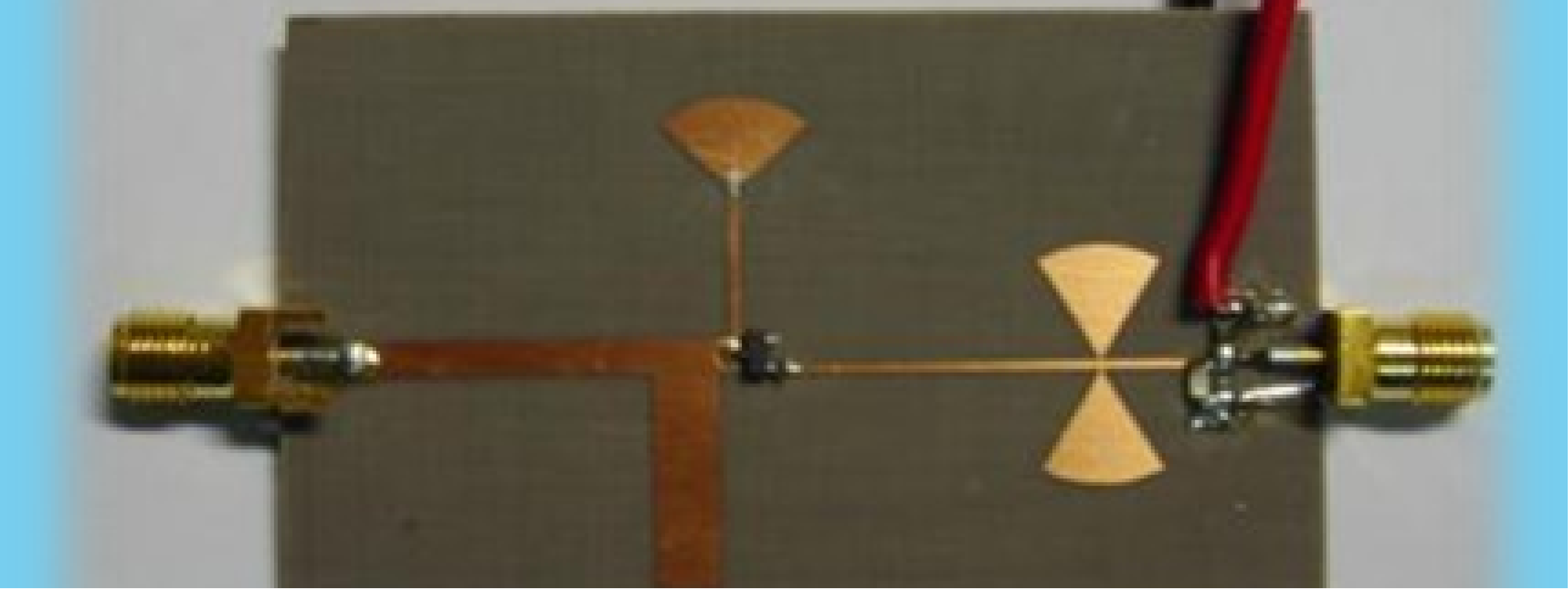




Two different loads

- The circuit is matched in one state (0 V) – **absorption state**;
- The circuit is mismatched in other state (1 V) – **reflection state**.

For -10 dBm (0.1 mW) of input power the output voltage generated is 0.487 V with 53.2 % of efficiency in the absorption state!
In the reflection state, the circuit can not generate any output voltage!

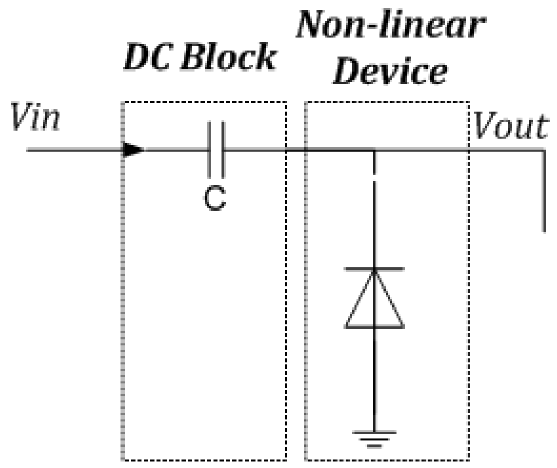


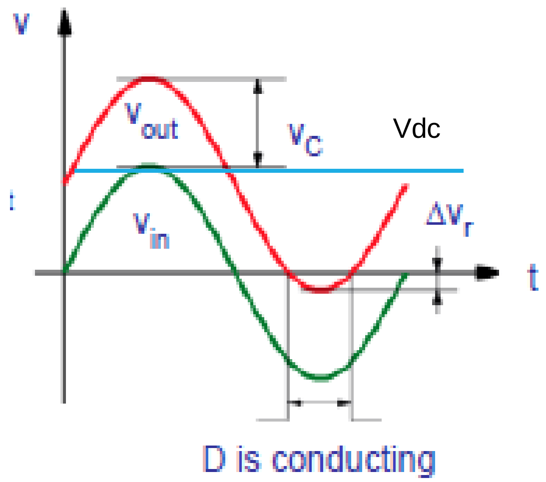
WIRELESS POWER TRANSMISSION

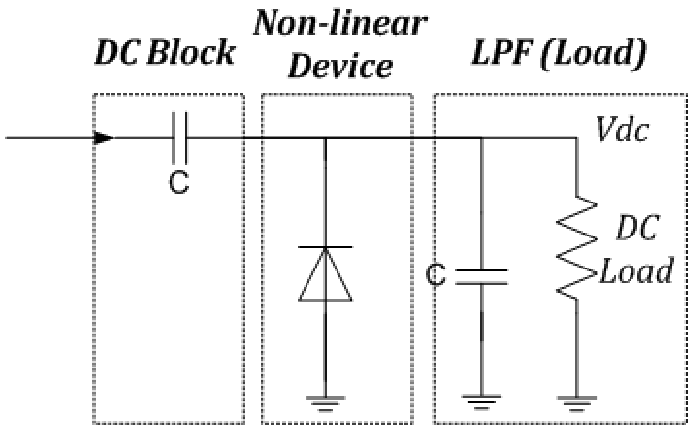
WIRELESS POWER TRANSMISSION

- ✓ Typically High Speed Schottky Diodes are used in RF-DC converters
- ✓ Commonly used configurations: single-diode detectors (high RF-DC efficiency), voltage multipliers (high voltage), full-wave rectifiers (current stability), …

Single-diode Envelope Detector







WIRELESS POWER TRANSMISSION

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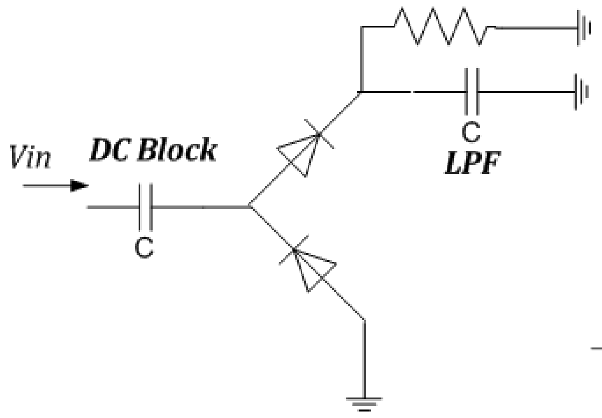
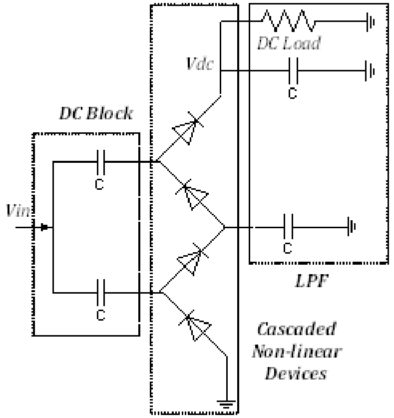
Half-wave Voltage Multipliers (Charge Pumps)

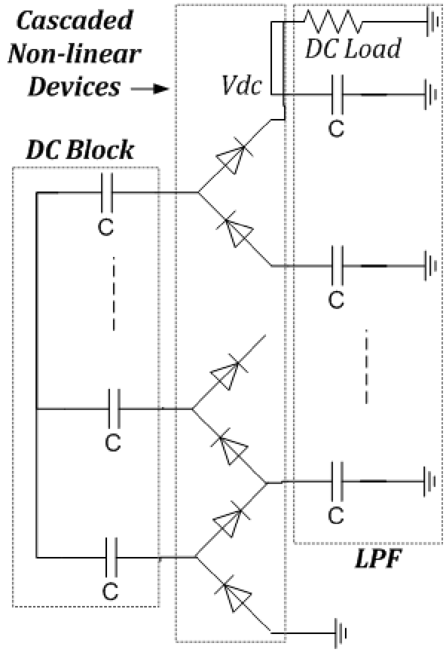
Voltage Doubler (1-stage)



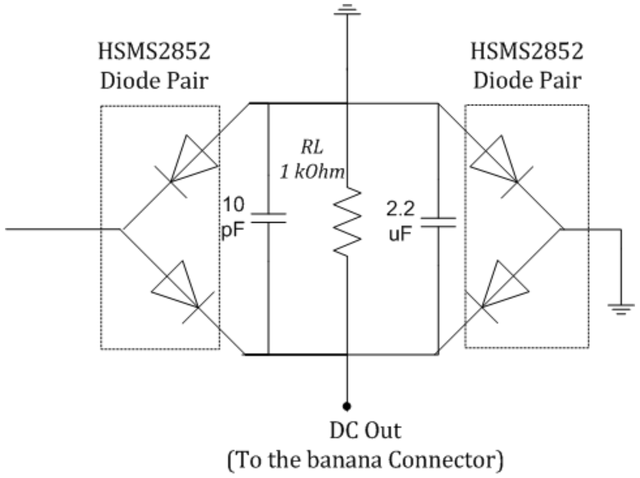
2-stages



N-stages

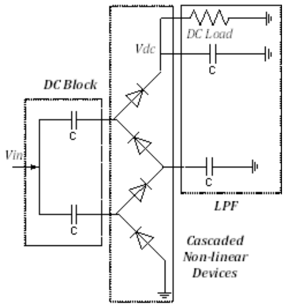


Full-wave Rectifiers

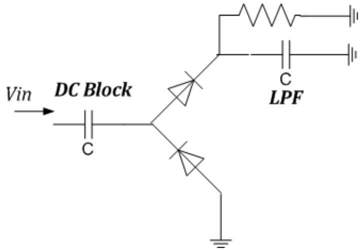


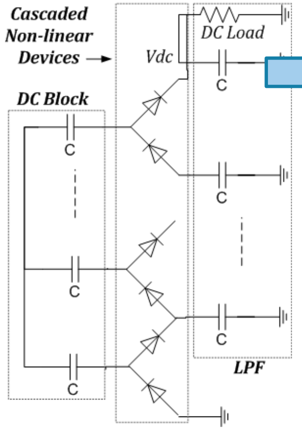
WIRELESS POWER TRANSMISSION

Non-linear Analysis of RF-DC Converters

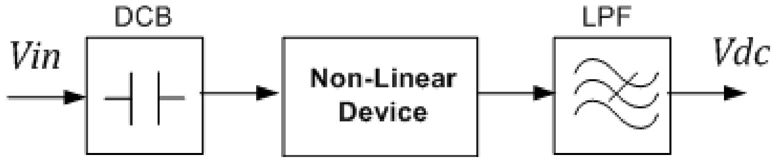


Any RF-DC Converter can be described by a non-linear Model:

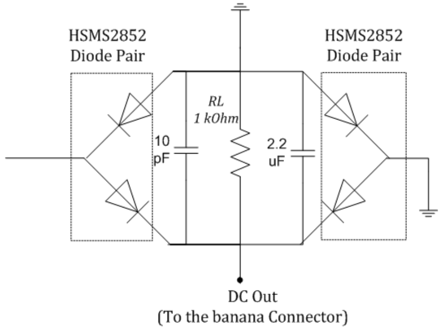


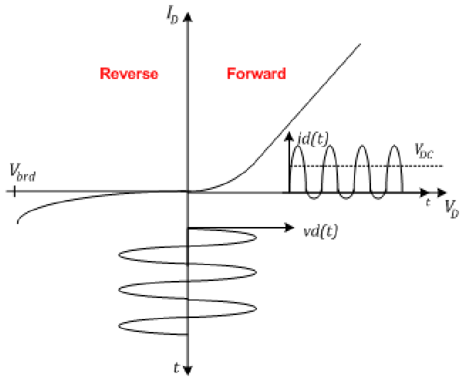


General Model



Diode Non-linear Characteristic (I-V Curve)





SENSOR RF-DC CONVERTER

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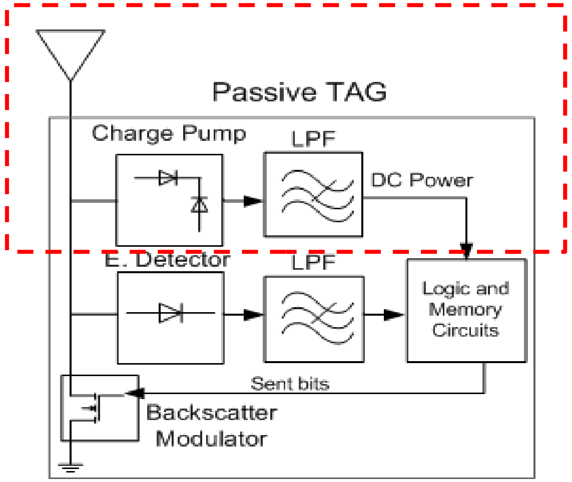
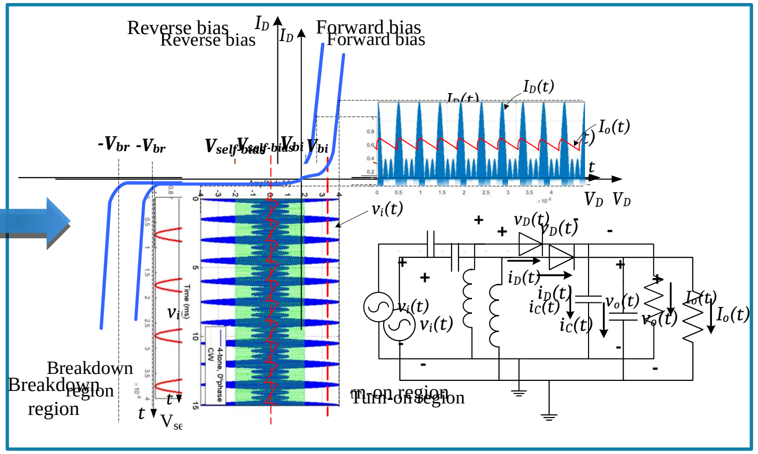
WPT Receiver



Desired component

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

RF-DC conversion process in a diode detector



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

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

A. Boaventura, D. Belo, R. Fernandes, A. Collado, A. Georgiadis and N. B. Carvalho, "Boosting the Efficiency: Unconventional Waveform Design for Efficient Wireless Power Transfer," in *IEEE Microwave Magazine*, vol. 16, no. 3, pp. 87-96, April 2015.

WIRELESS POWER COMMUNICATIONS

BACKSCATTER BATTERY-LESS PARADIGM

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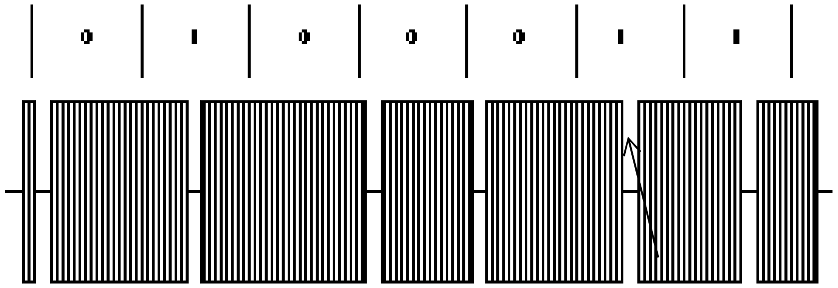
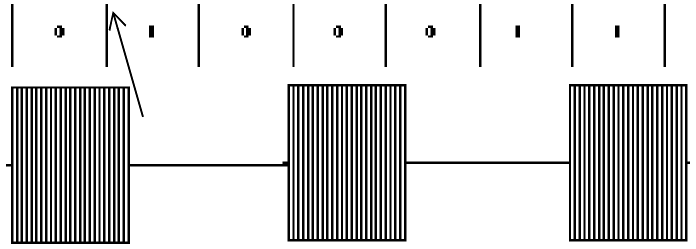
Access Point-to-sensor link has two goals

- Communication
- Energy transfer

Data communication and Energy transfer can take place simultaneously

- In such cases the Modulation and Codification must be carefully designed, otherwise the Energy transfer will be degraded
- An inappropriate combination of Codification-Modulation with long dead periods (signal off) would lead the tag to fail





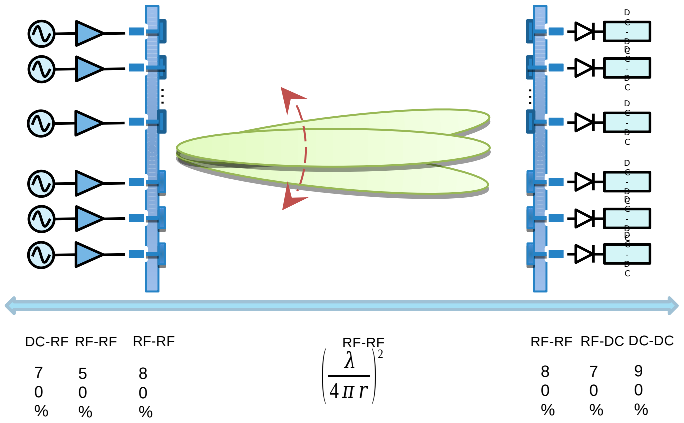
Good choice: signal is off for short periods of time

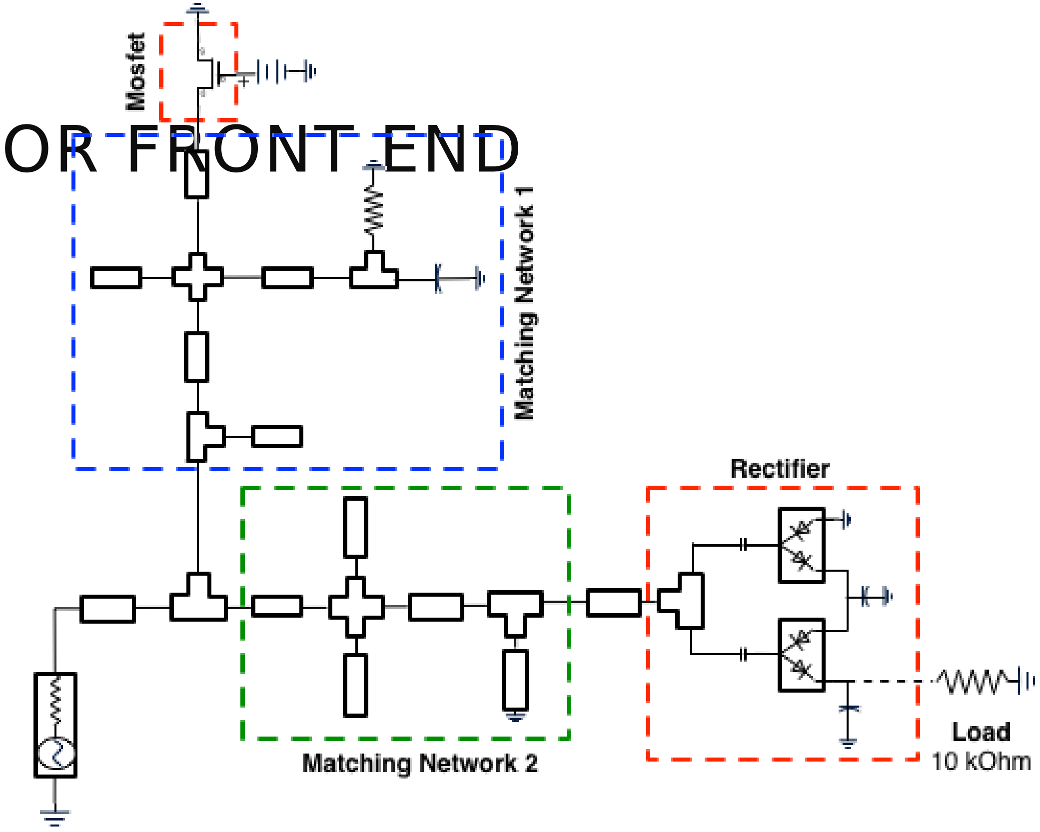
Bad choice: signal is off for long periods of time

- At those periods tag has no available energy to operate

BACKSCATTER SENSOR FRONT END

Combining WPT and Backscatter using dual band sensors

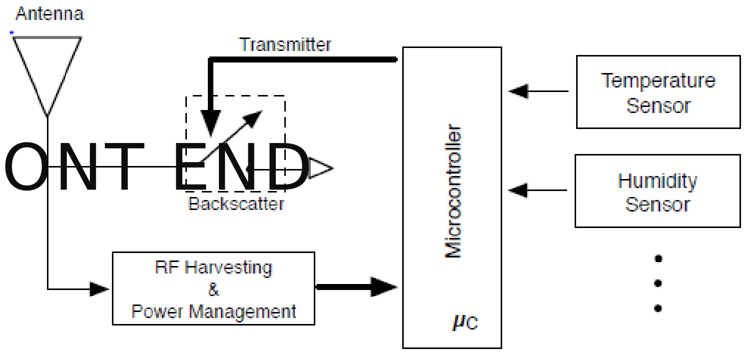


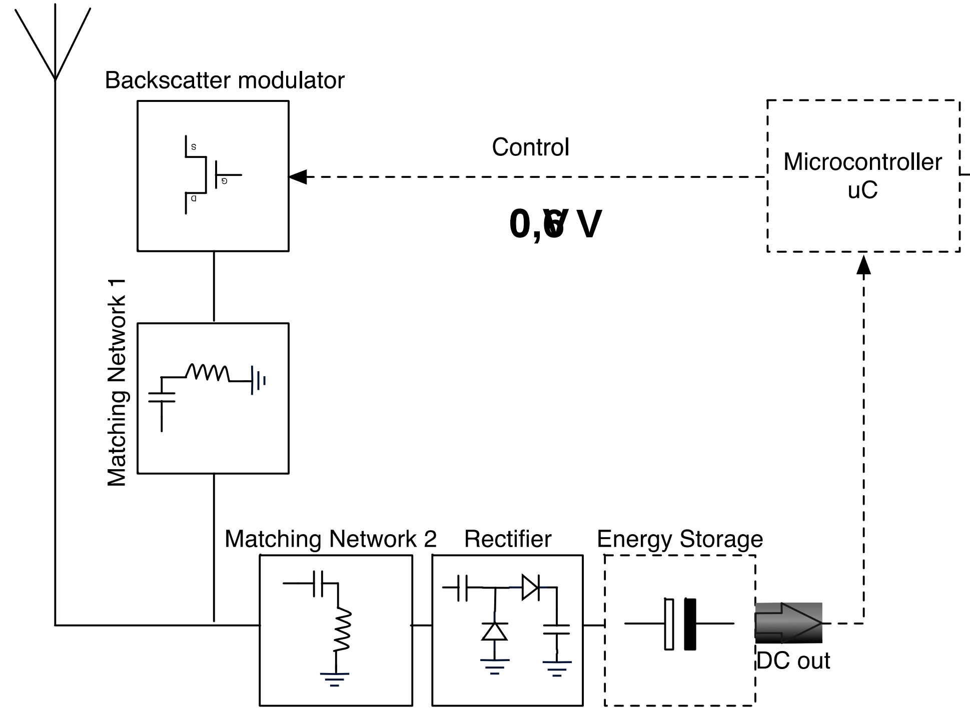


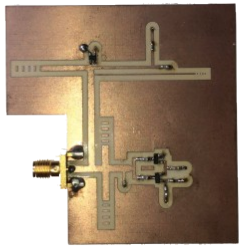
ONE frequency for WPT and OTHER for backscatter

R. Correia, N. Borges Carvalho and S. Kawasaki, "Continuously Power Delivering for Passive Backscatter Wireless Sensor Networks," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 11, pp. 3723-3731, Nov. 2016.

BACKSCATTER SENSOR FRONT END

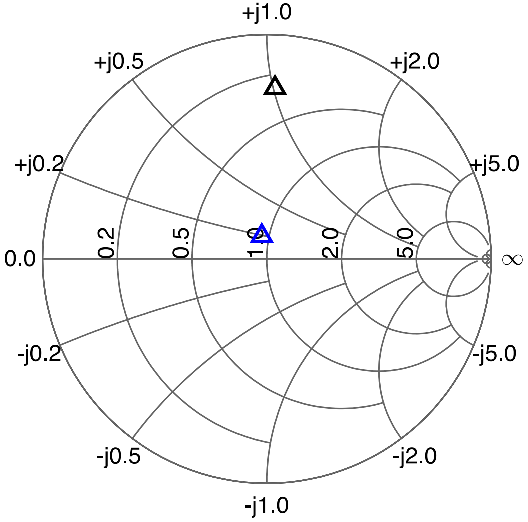






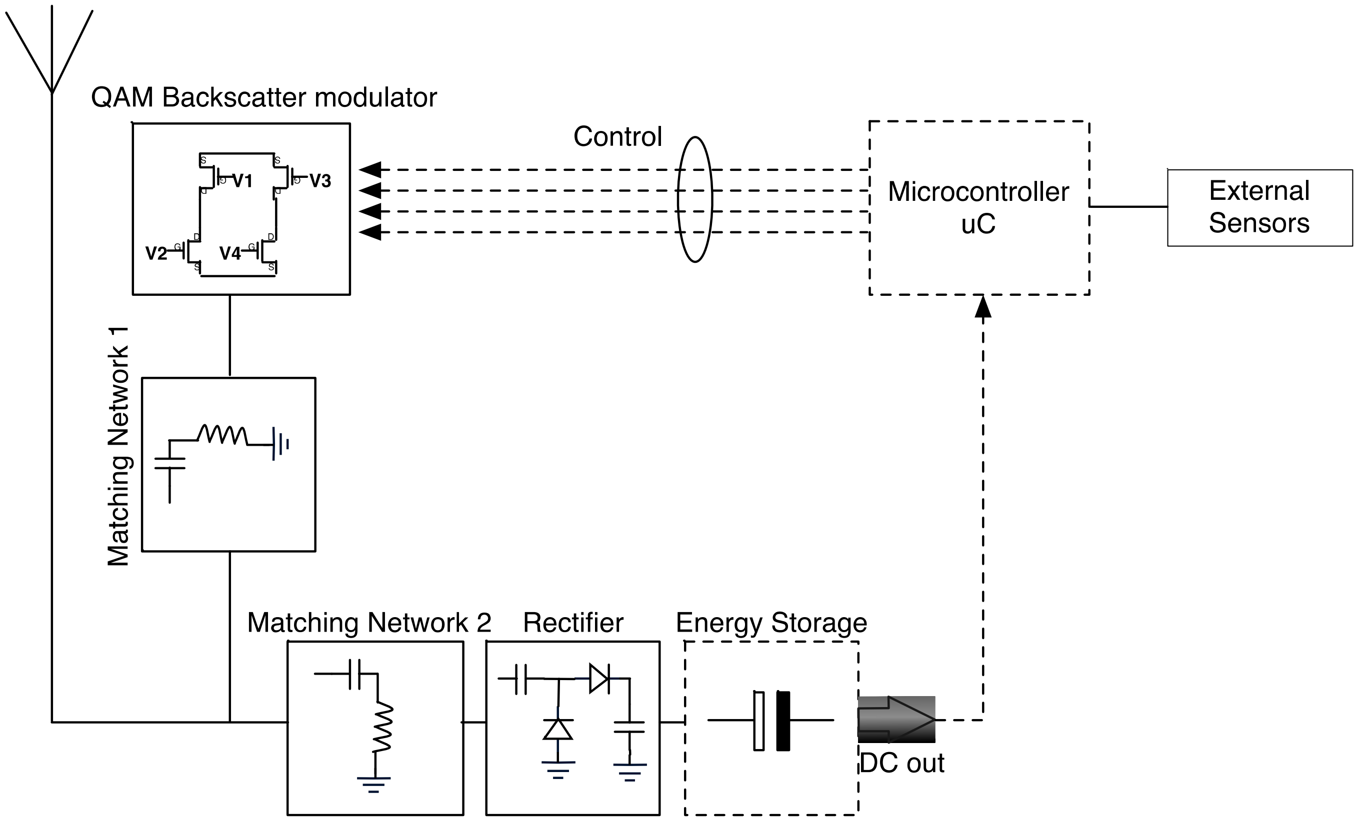
F1 = 1.8 GHz

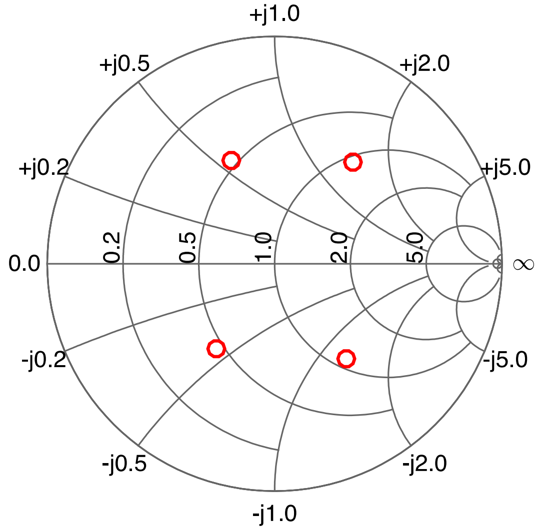
F2 = 2.45 GHz



R. Correia, N. Borges Carvalho and S. Kawasaki, "Continuously Power Delivering for Passive Backscatter Wireless Sensor Networks," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 11, pp. 3723-3731, Nov. 2016.

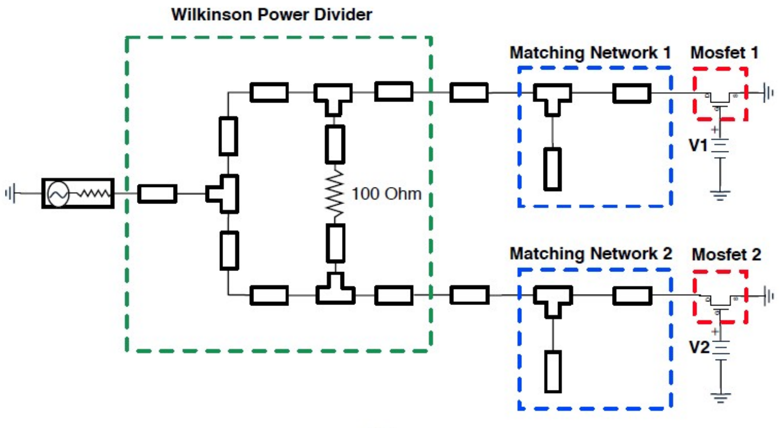
BACKSCATTER SENSOR FRONT END – HIGHER ORDER MODULATION





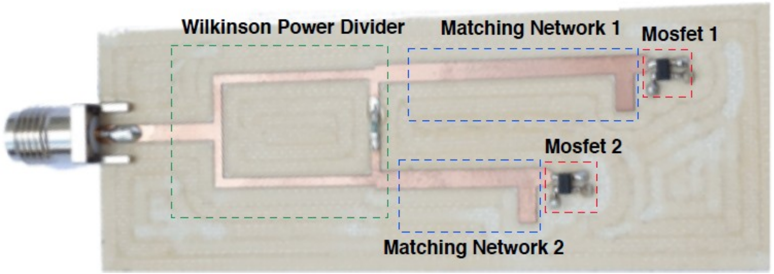
R. Correia and N. B. Carvalho, "Design of high order modulation backscatter wireless sensor for passive IoT solutions," *2016 IEEE Wireless Power Transfer Conference (WPTC)*, Aveiro, 2016, pp. 1-3.

BACKSCATTER SENSOR FRONT END – EXPERIMENTAL RESULTS

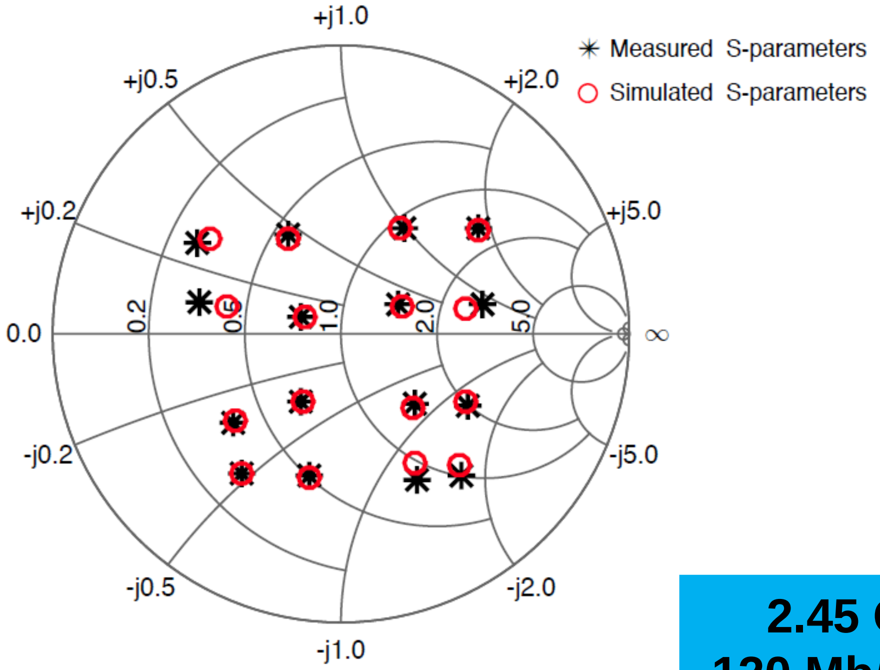


(a)

IQ Backscatter Modulator



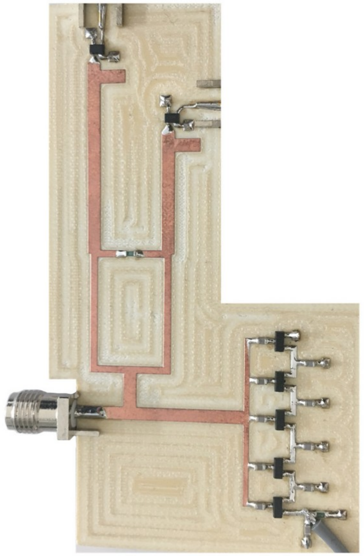
(b)

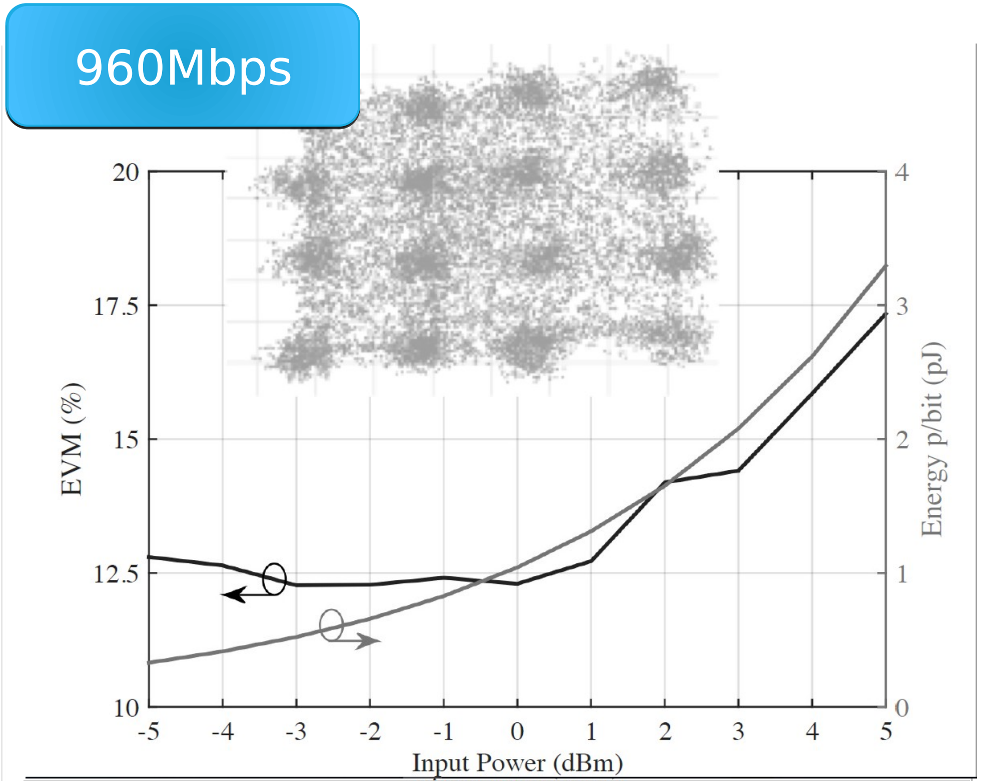


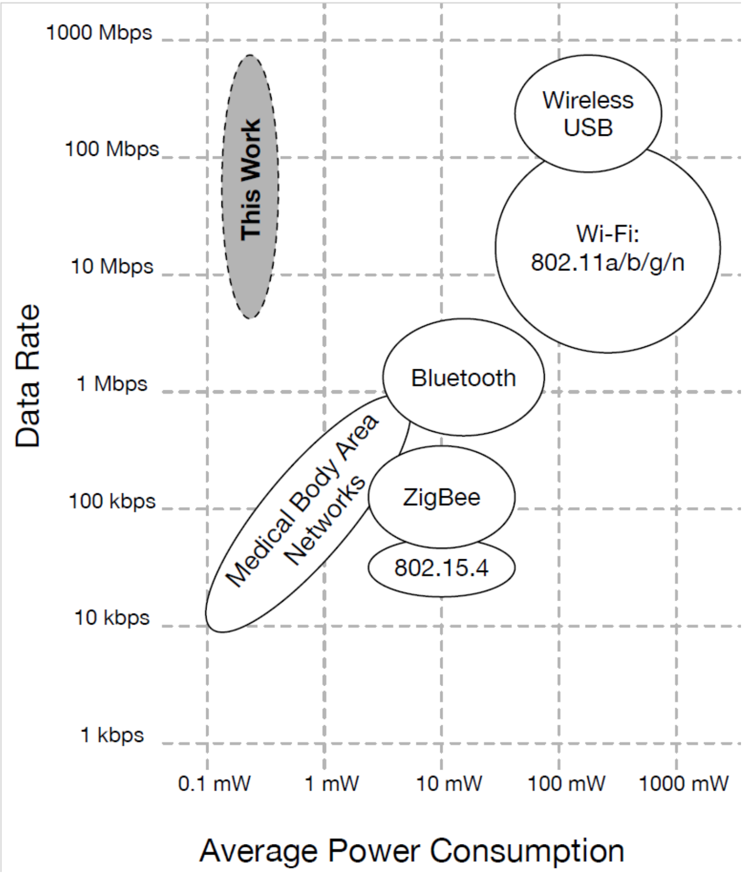
2.45 GHz
120 Mb/s with
6.7pJ/bit

R. Correia; A. Boaventura; N. B. Carvalho, "Quadrature Amplitude Backscatter Modulator for Passive Wireless Sensors in IoT Applications," in *IEEE Transactions on Microwave Theory and Techniques* , vol.PP, no.99, pp.1-8

BACKSCATTER SENSOR FRONT END – EXPERIMENTAL RESULTS







2.45 GHz
960 Mb/s with
0,9 pJ/bit

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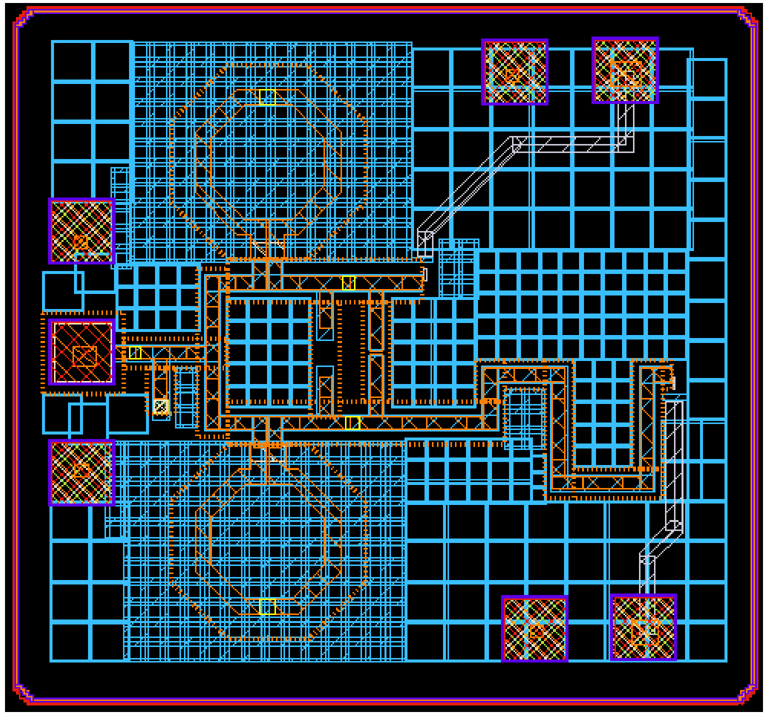
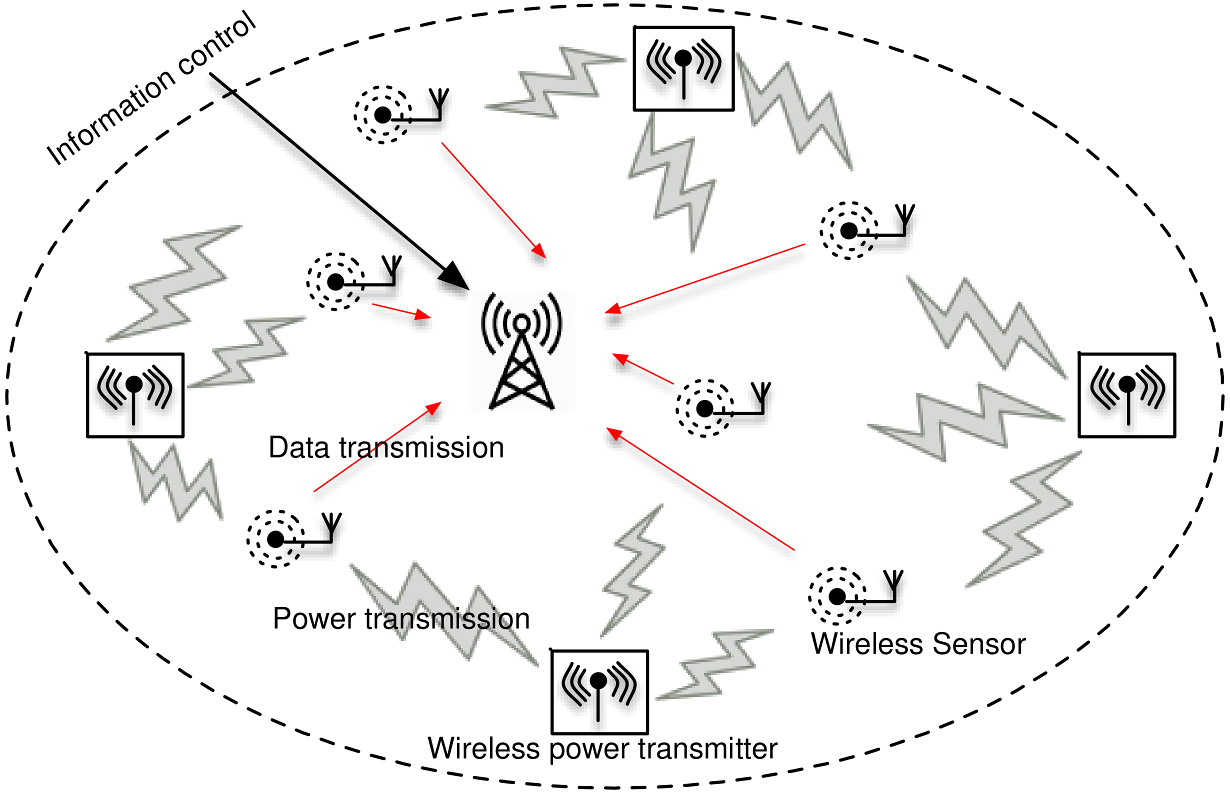
BACKSCATTER SENSOR FRONT END – EXPERIMENTAL RESULTS

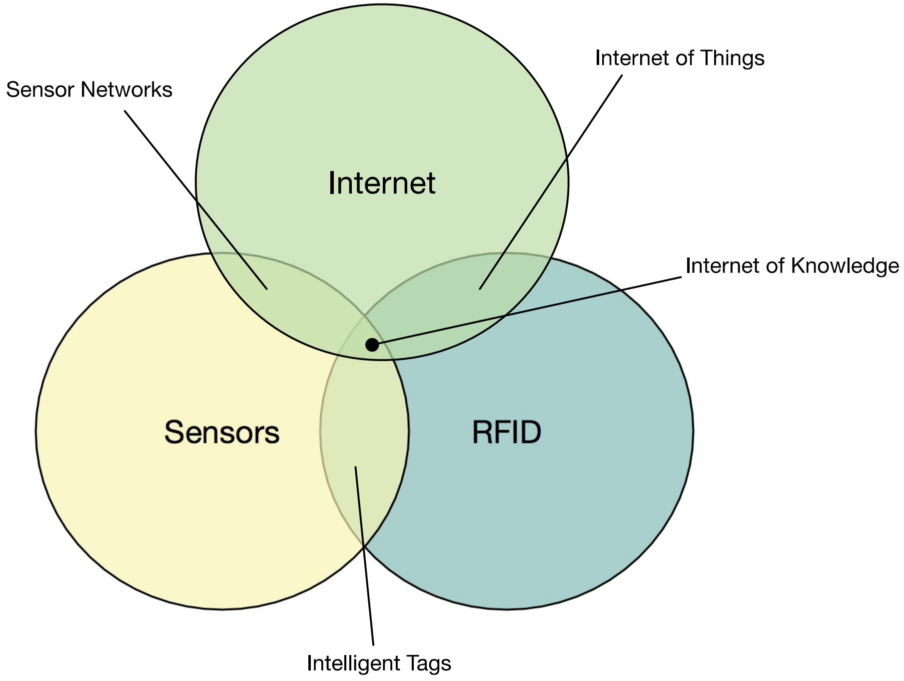
Design an MMIC chip for higher frequencies based on high order backscatter modulation.



SiGe BICMOS
SG13S
technology
0.92 mm²

SWIPT – THE FUTURE





Solution for totally passive WSNs

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BACKSCATTER - APPLICATIONS

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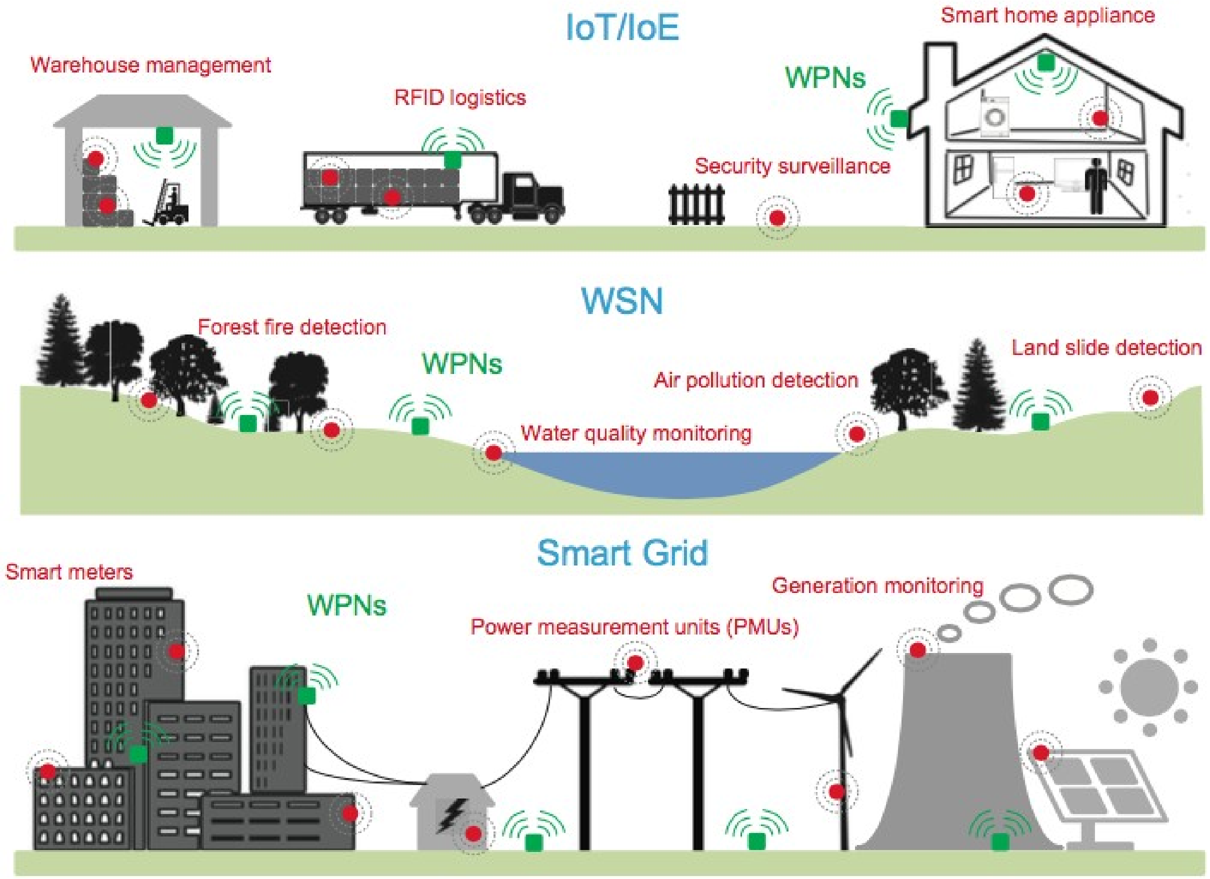

WPC (Wireless Power Communication) will be an important building block of many popular commercial and industrial systems in the future, including the upcoming IoT/IoE systems consisting of billions of sensing/RFID devices as well as large-scale WSNs.

Figure taken from S. Bi, C. K. Ho, and R. Zhang, “Wireless powered communication: opportunities and challenges,” *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 117–125, Apr. 2015.

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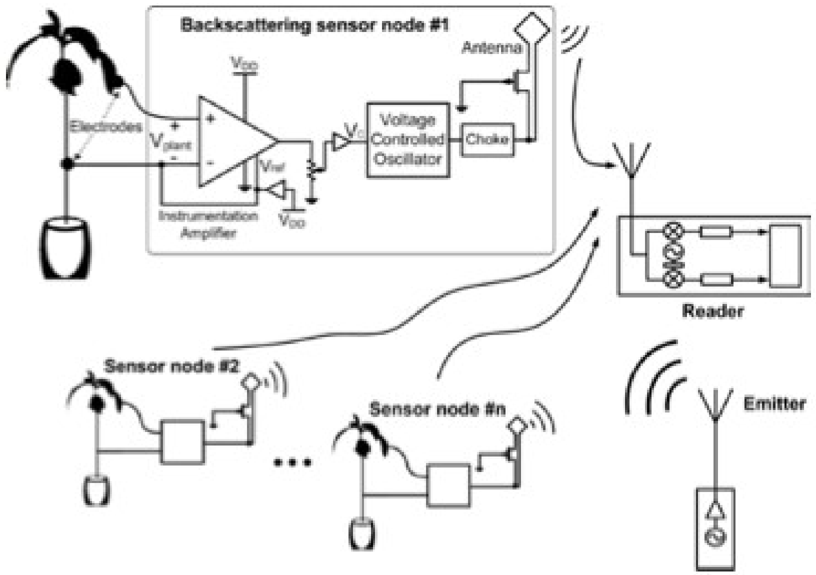
BACKSCATTER - APPLICATIONS

Wireless Sensor Node for Backscattering Electrical Signals generated by Plants

- Measures the electrical signal of the plant and backscatters the sensed information to a central reader

- Several WSN sensor nodes
- Carrier emitter
- Reader

} Bistatic Architecture



Backscattering Modulator

- Antenna and a switching transistor controlled by square-wave signal

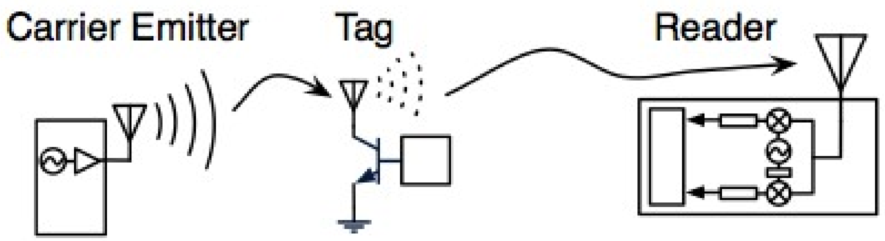
ON → Incoming carrier signal is reflected by antenna and scattered back to the reader (π phase-difference)

OFF → Received signal is reflected back to the reader (zero phase)

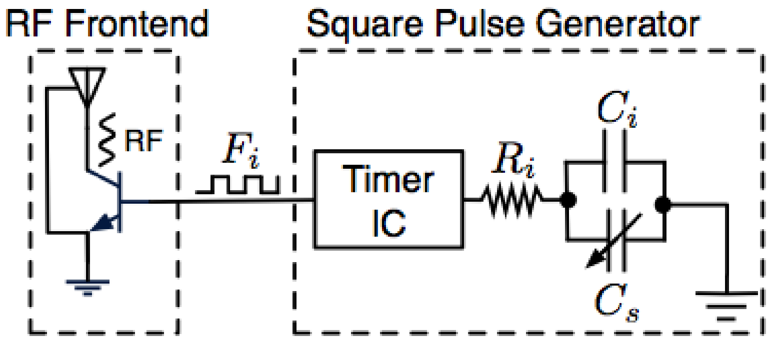
BACKSCATTER - APPLICATIONS

Backscatter Sensor Network for Extended Ranges and Low Cost with frequency modulation: Application on Wireless Humidity Sensing

- Low complexity
- Low power
- Low cost



Based on low-cost and low-power relative humidity (%RH) to frequency modulator



$$F_i = \frac{1}{\ln 2 R_i (C_i + C_s)}$$

→ Each i-th tag can occupy bandwidth on the order of few kHz and is allocated a unique subcarrier frequency center, by selecting a specific pair of R_i,C_i

Timer acts as a generator of variable frequency pulser based on %RH

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LORA BACKSCATTER

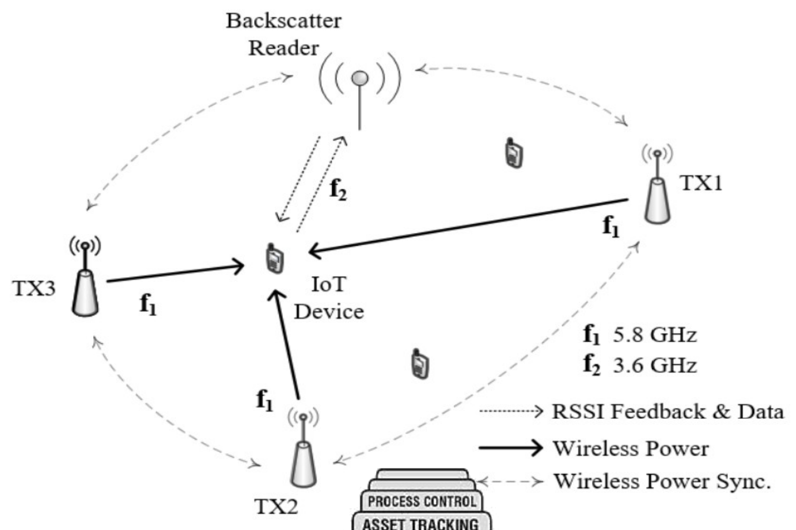
LONG RANGE (LORA) BACKSCATTER COMMUNICATIONS

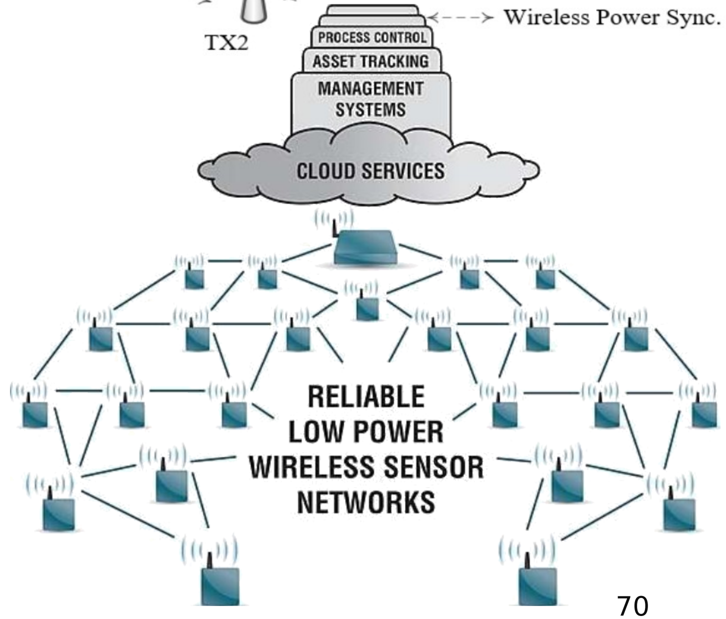
- Recall the distributed WPT scenario…
  - Several WPT beacons, high gain antennas
  - **Fewer** backscatter readers with low gain antennas

In that situation, the operating range is no longer limited by the WPT link

- It is desirable to provide **long range** as well as **low power** communications

Not so simple to achieve both simultaneously!



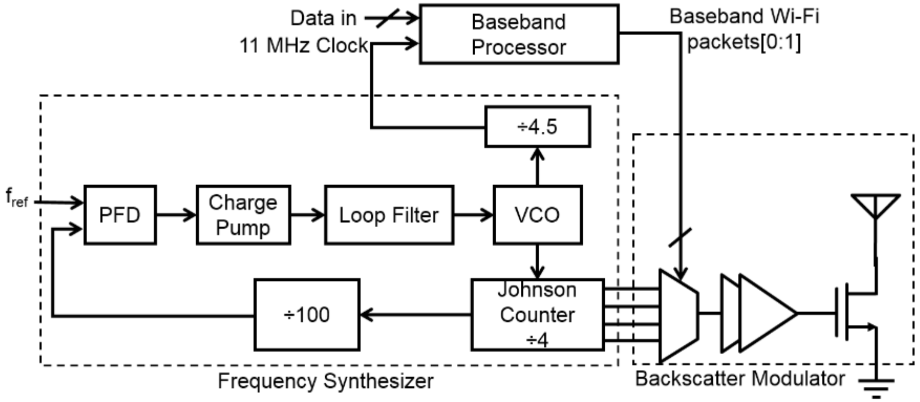


https://www.edn.com/design/analog/4426319/Low-Power-wireless-sensor-networks-for-the-Internet-of-Things-

LONG RANGE (LORA) BACKSCATTER COMMUNICATIONS

- Most common low power modulations used in IoT applications
- **Sensitivity - Range**
- Is it possible to generate those **modulations** with **backscattering techniques**?

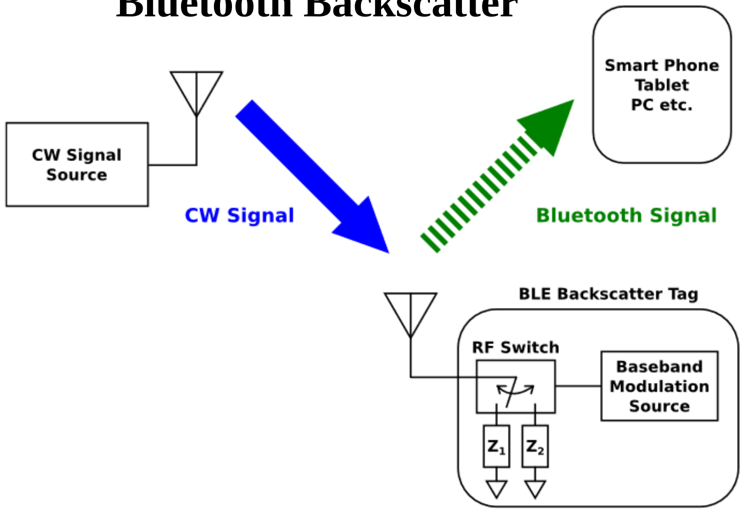
Technology	Sensitivity	Data Rate
LoRa	-149 dBm	18 bps - 37.5 kbps
Sigfox	-126 dBm	100 bps
NB-IoT	-129 dBm	0.6 - 250 kbps
Wi-Fi (802.11 b/g)	-95 dBm	1 - 54 Mbps
Bluetooth	-97 dBm	1 - 2 Mbps
ZigBee	-100 dBm	250 kbps
RFID	-85 dBm	40 - 640 kbps



Wi-Fi Backscatter

	1 Mbps	11 Mbps
Baseband Frequency Synthesizer	5.6 μW	5.6 μW
Baseband Processor	5.0 μW	48 μW
Backscatter Modulator	3.9 μW	5.6 μW
Total Power	14.5 μW	59.2 μW

Bluetooth Backscatter



B. Kellogg, V. Talla, J. R. Smith, and S. Gollakot, "PASSIVE WI-FI: Bringing low power to Wi-Fi transmissions," *GetMobile Mob. Comput. Commun.*, vol. 20, no. 3, pp. 38–41, Jan. 2017.

J. F. Ensworth and M. S. Reynolds, "BLE-Backscatter: Ultralow-power IoT nodes compatible with Bluetooth 4.0 Low Energy (BLE) smartphones and tablets," IEEE Trans. Microw. Theory Tech., vol. 65, no. 9, pp. 3360–3368, Sep. 2017

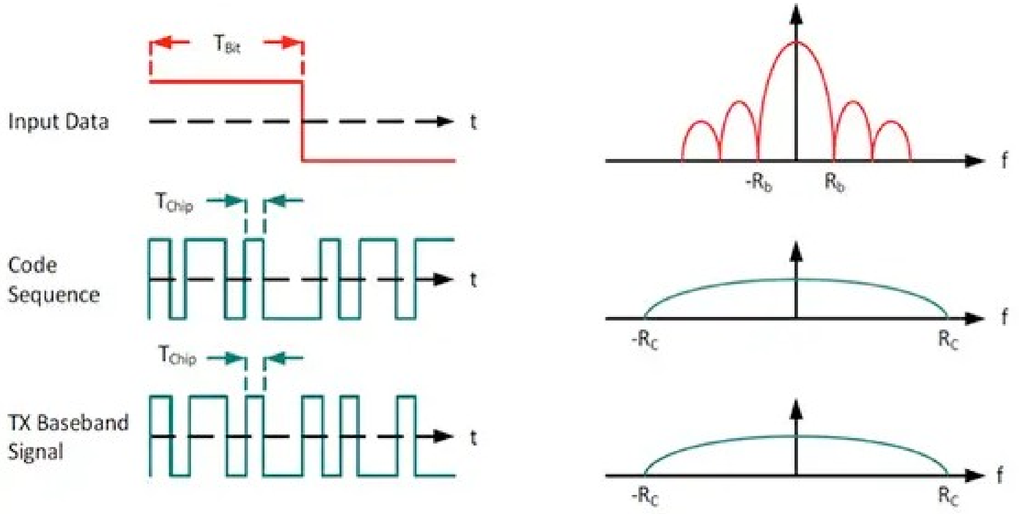
LONG RANGE (LORA) BACKSCATTER COMMUNICATIONS

- **LoRa** from **Semtech** provides the highest currently available sensitivity

Technology	Sensitivity	Data Rate
LoRa	-149 dBm	18 bps - 37.5 kbps
Sigfox	-126 dBm	100 bps
[illegible]	[illegible]	[illegible]

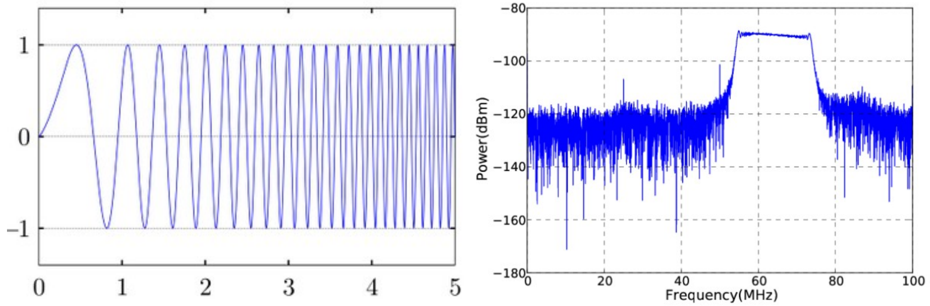
- **Relies on Spread Spectrum techniques**
  - Resilient to external interference
  - Less sensitive to multipath fading
  - Co-existence with other systems
  - Hard to detect/demodulate

DSSS

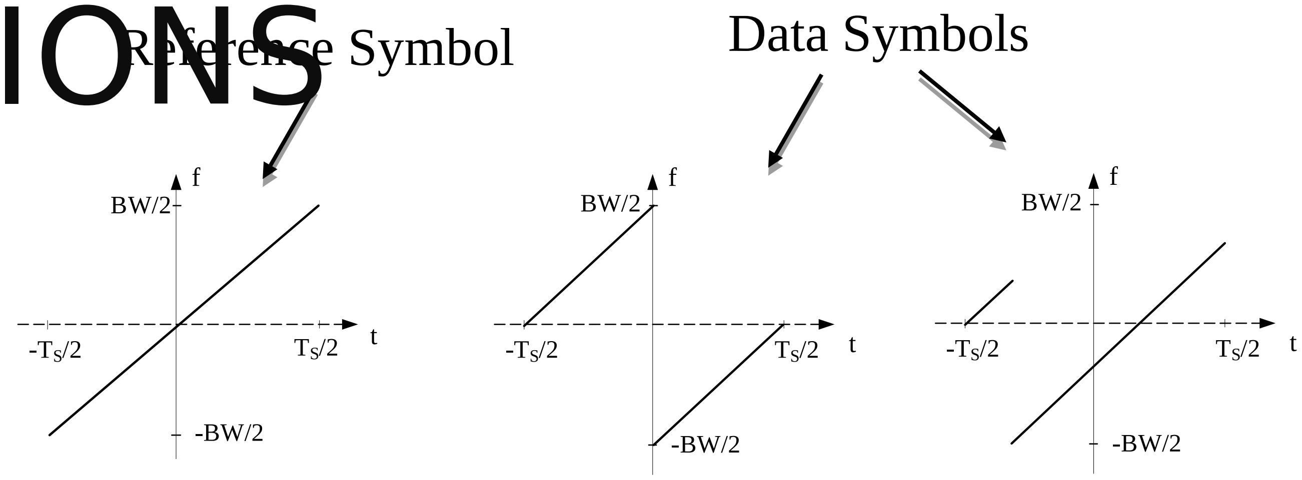


- **Chirp Spread Spectrum**

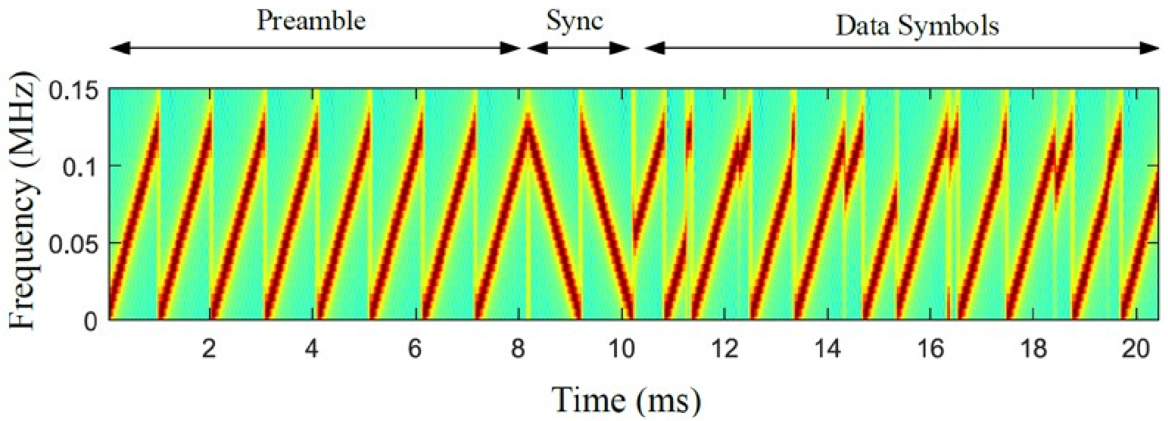
CSS



LONG RANGE (LORA) BACKSCATTER COMMUNICATIONS



- LoRa is a special case of chirp spread spectrum modulation
- **Cyclic shifts** are introduced to encode data
- **Bit rate:** $R_b = SF \frac{BW}{2^{SF}}$
  - SF is the spreading factor (7…12)
  - BW is the bandwidth of the chirp (125, 250 or 500 kHz)



- **chips/symb** ⇒ possible cyclic shifts (each symbol carries SF bits)

LORA BACKSCATTER COMMUNICATIONS

- The baseband **reference symbol** is represented by

$$s(t) = e^{j\phi(t)}$$

- The **instantaneous frequency** of the signal, , must increase linearly with time…

$$f(t) = \frac{BW}{T_s} t \text{ , where } \quad T_s = \frac{2^{SF}}{BW} \qquad f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}$$

Thus, the **phase progression** required to generate a linear frequency modulated signal (chirp) is given by

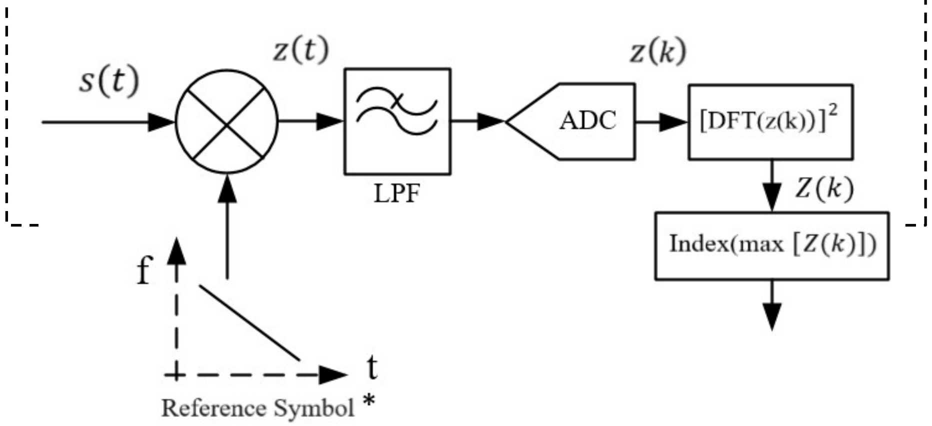
$$\phi(t) = \phi_0 + 2\pi\int_0^t f(\tau)d\tau = \phi_0 + \pi\frac{BW}{T_s}t^2$$

Demodulation

$$z(t) = s(t)e^{-j\left(\phi_0+\pi\frac{BW}{T_s}t^2\right)}$$

$$z[k = T_s/m]$$

$$k = 1,2,\dots,2^{SF} \quad m = 2^{SF},\dots,2,1$$

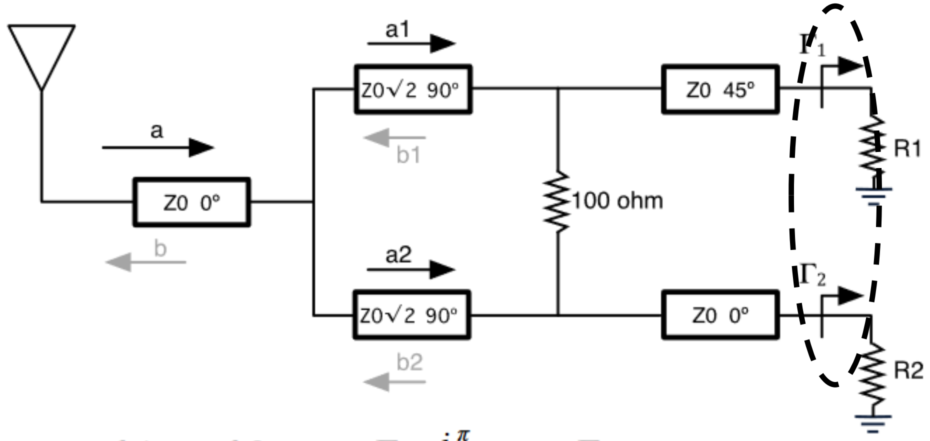


Index(max

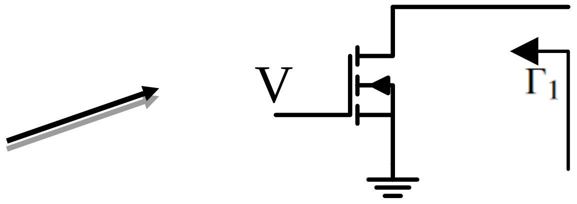
Can be efficiently generated with backscattering techniques

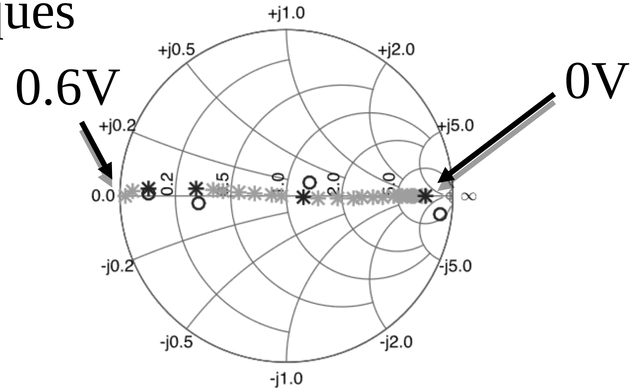
LORA BACKSCATTER COMMUNICATIONS

- It is required to **efficiently** generate **complex signals** with backscattering techniques



Variable load



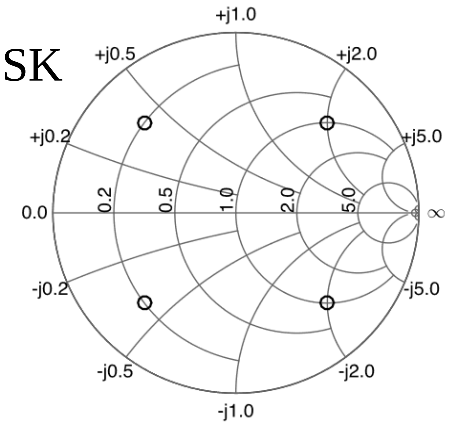


$$b = \frac{b1}{\sqrt{2}} + \frac{b2}{\sqrt{2}} = \frac{a_1 \Gamma_1 e^{j\frac{\pi}{2}}}{\sqrt{2}} + \frac{a_2 \Gamma_2}{\sqrt{2}}$$

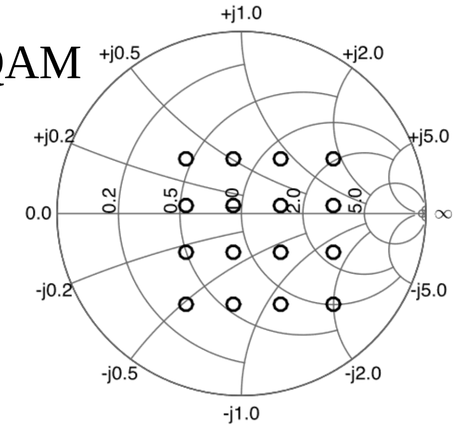
$$\Gamma_1 = \frac{R_1 - Z_0}{R_1 + Z_0} \qquad \Gamma_2 = \frac{R_2 - Z_0}{R_2 + Z_0}$$

$$\Gamma = \frac{b}{a} = \frac{\Gamma_1 \frac{1}{\sqrt{2}}}{\sqrt{2}} e^{j\frac{\pi}{2}} + \frac{\Gamma_2 \frac{1}{\sqrt{2}}}{\sqrt{2}} \Rightarrow \Gamma = \frac{\Gamma_2}{2} + j\frac{\Gamma_1}{2}$$

QPSK



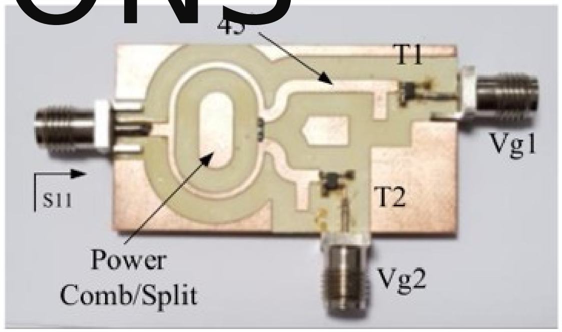
16-QAM

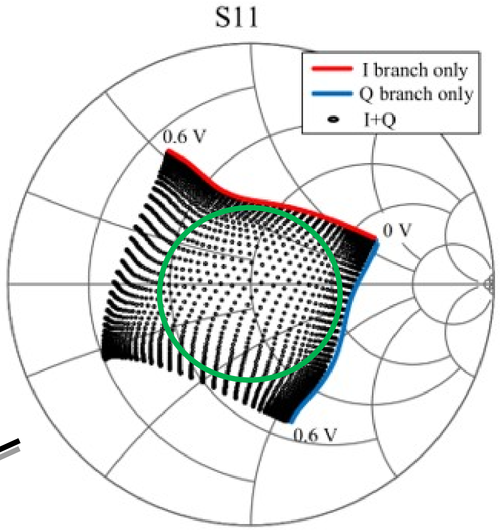


R. Correia, A. Boaventura, and N. B. Carvalho, “Quadrature amplitude backscatter modulator for passive wireless sensors in IoT applications,” *IEEE Trans. Microw. Theory Tech.*, pp. 1–8, Feb. 2017.

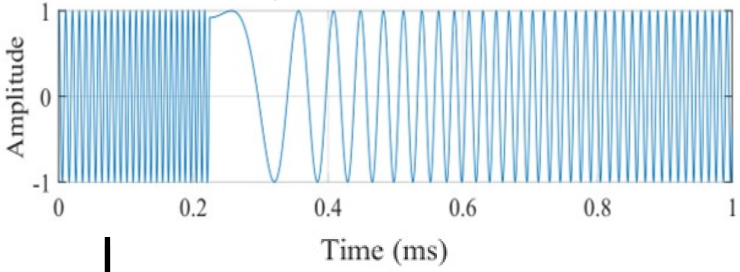
LORA BACKSCATTER COMMUNICATIONS

- **Characterization @ 2.45 GHz** (mesh of 1x1 mV)
- **Non-Linear Transformation**

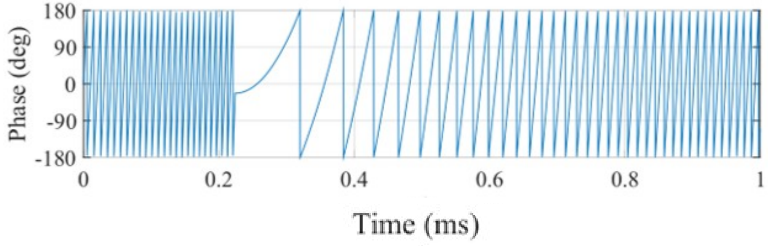


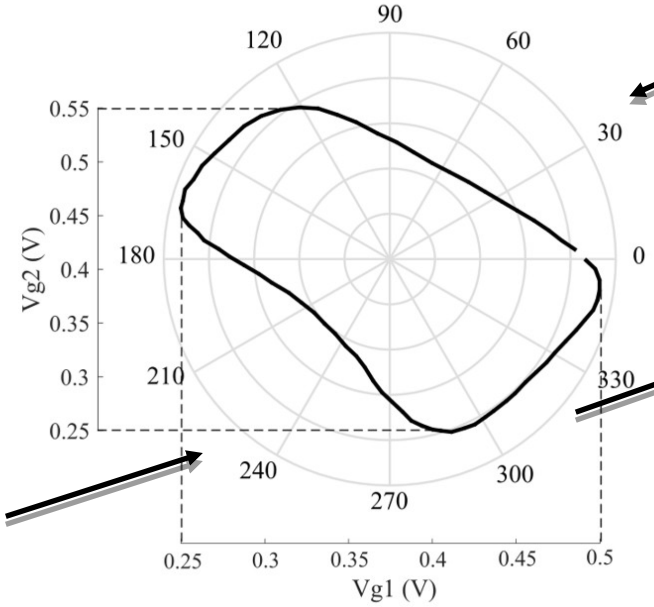


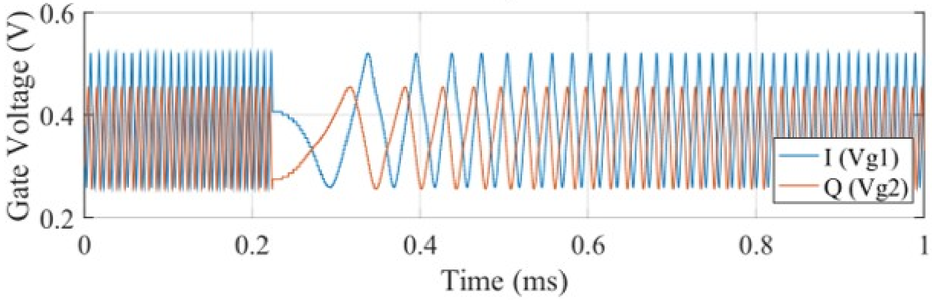
Symbol index 44



$$\phi(t) = \phi_0 + \pi \frac{BW}{T_s} t^2$$







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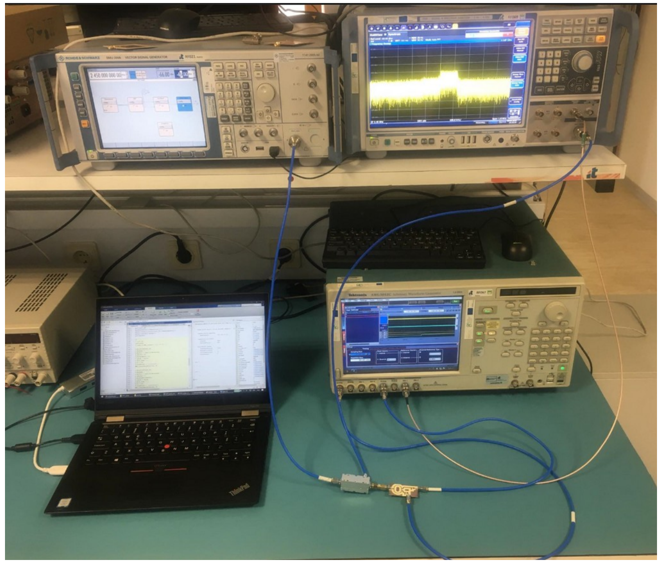
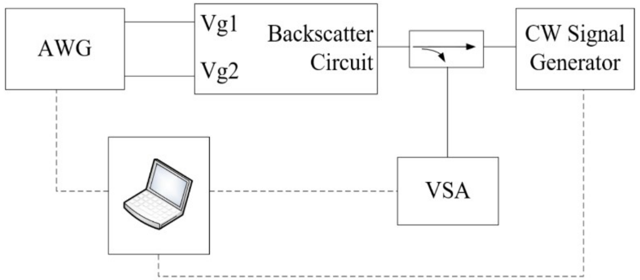
LORA BACKSCATTER COMMUNICATIONS

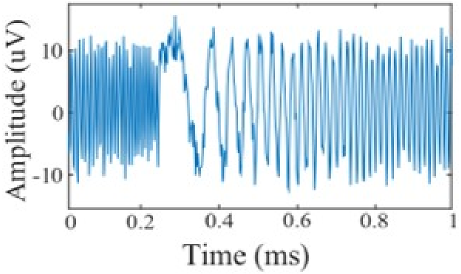
- **Cable measurements**
- 12,000 random symbols
- V_{G1} and V_{G2} generated with MATLAB and loaded to an AWG
- VSA down-converts to the complex baseband
- IQ loaded to MATLAB and decoded

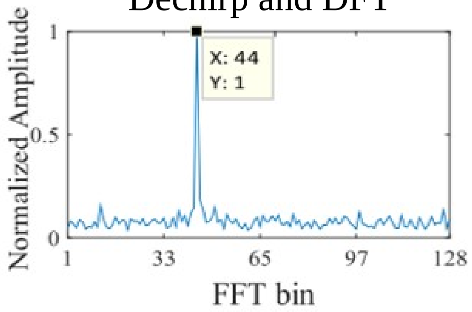




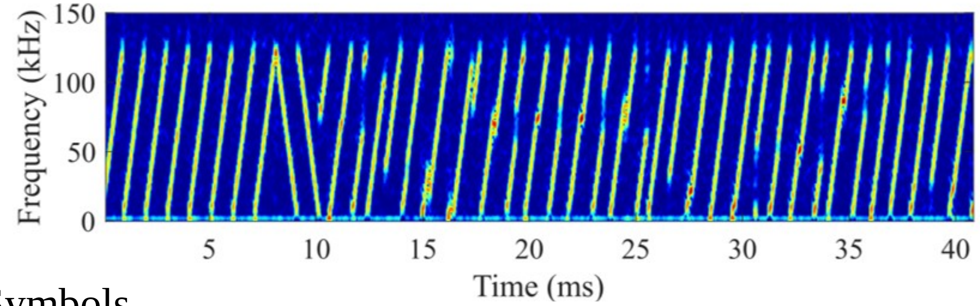
Symbol index 44
Sampled by the VSA

MATLAB
Dechirp and DFT





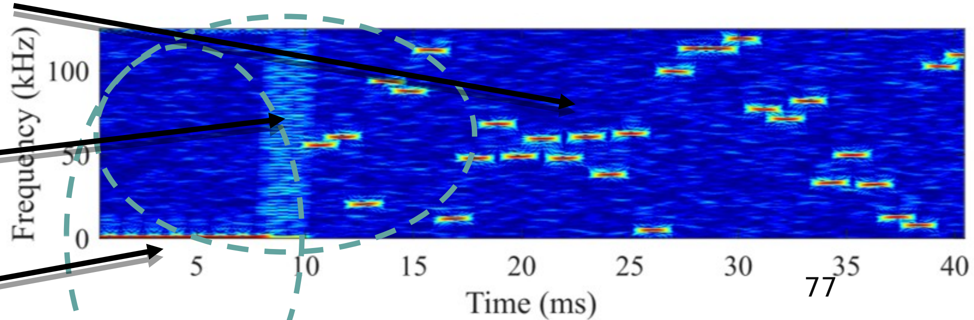
Fist 40 received symbols @ 9 dB SNR



Data Symbols

Synchronization Symbols

Preamble Symbols



LORA BACKSCATTER COMMUNICATIONS

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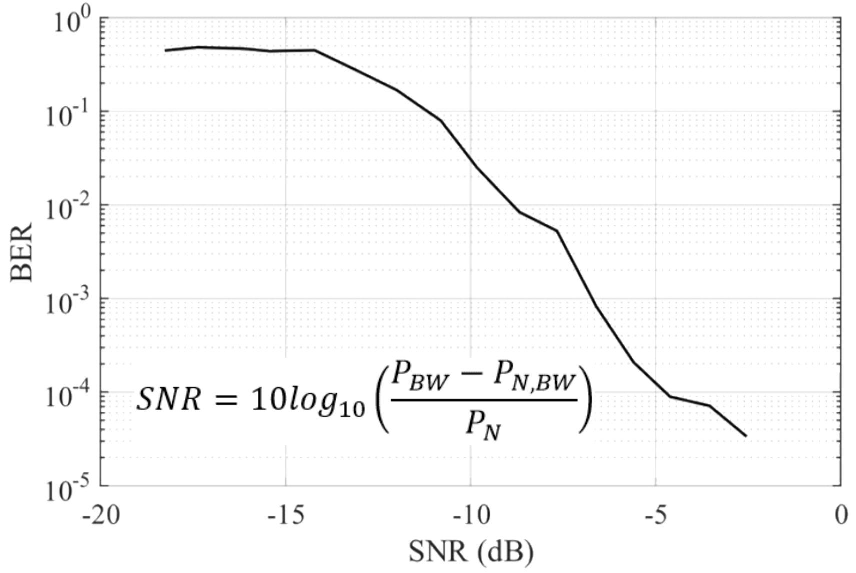
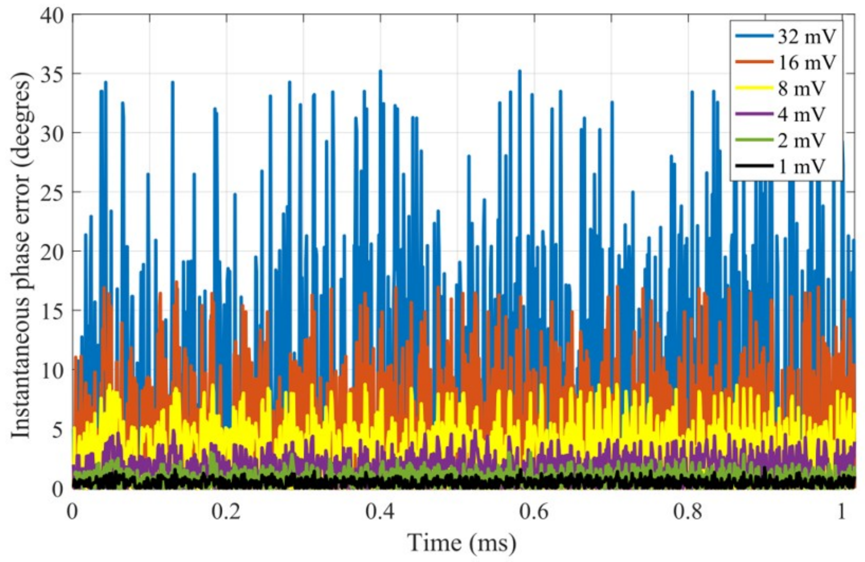
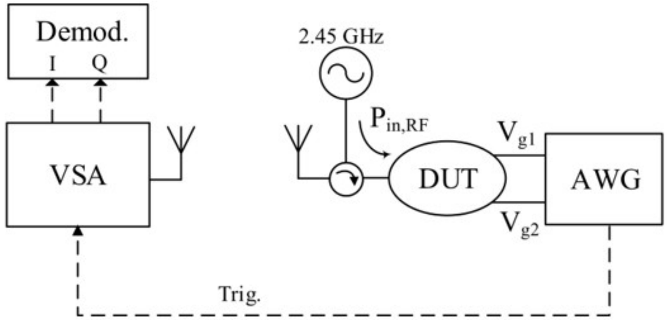
- **BER** estimation
  - 125 kHz LoRa BW
  - Sampled by the VSA at 4*BW in order to obtain an estimation of the noise power
  - Down-converted in MATLAB to exactly BW Hz
  - 12,000 Symbols transmitted several times for each value of SNR

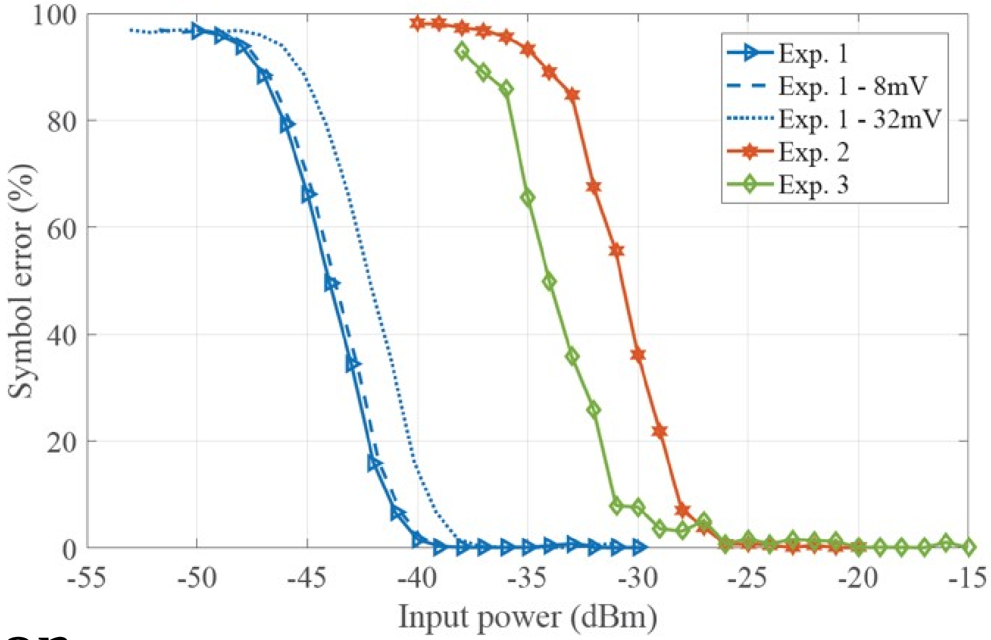


- **Control voltage sensitivity**
  - Perturbations intentionally added to the control voltages, 1, 2, 4 ,8 ,16 and 32 mV



LORA BACKSCATTER COMMUNICATIONS





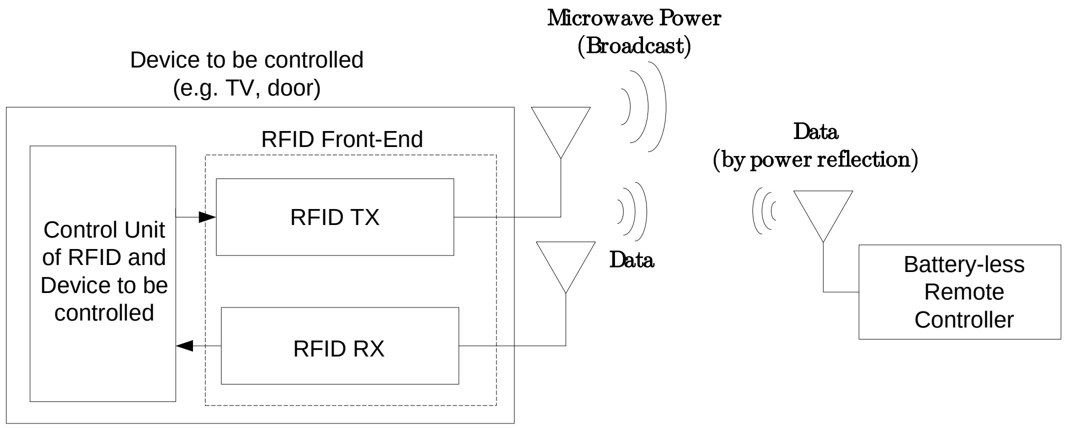
- **Over-the-Air** Evaluation
  - **Exp. 1** – Typical indoor scenario with LOS conditions, ~10 m
  - **Exp. 2** – Desks and laboratorial hardware in between the antennas, ~7.5 m
  - **Exp. 3** – A wall in between the antennas, ~10 m

APPLICATIONS: PASSIVE REMOTE CONTROL

BATTERY-LESS REMOTE CONTROL

A battery-free **Remote Control System** is proposed:

- The Remote requires no battery, based on passive RFID technology
- Device to be Controlled wirelessly powers the remote control using radio waves
- The remote control send back information using Backscattering (Power reflection)

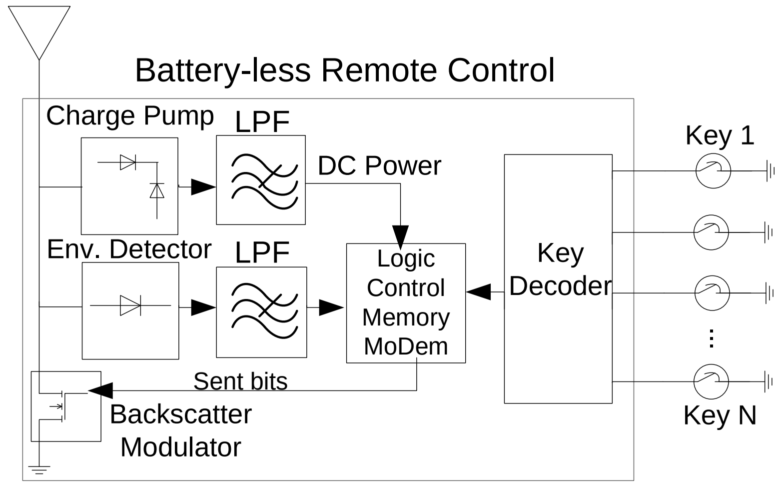


Advantages compared to conventional IR technology:

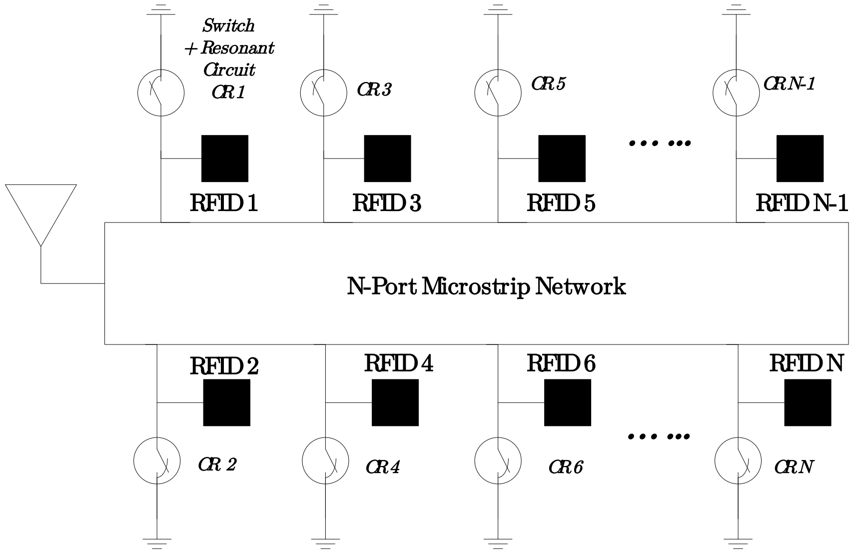
- ✓ **Elimination of costs** associated to battery maintenance and treatment of toxic waste
- ✓ **Long range and no line of sight communication** thanks to the use of radio waves
- ✓ **Cost-effective solution**, thanks to the use of a low-cost RFID technology (UHF EPC)

PROPOSED SOLUTIONS

Option I: Passive Wireless Sensor - alike



Option II: Multi-RFID scheme



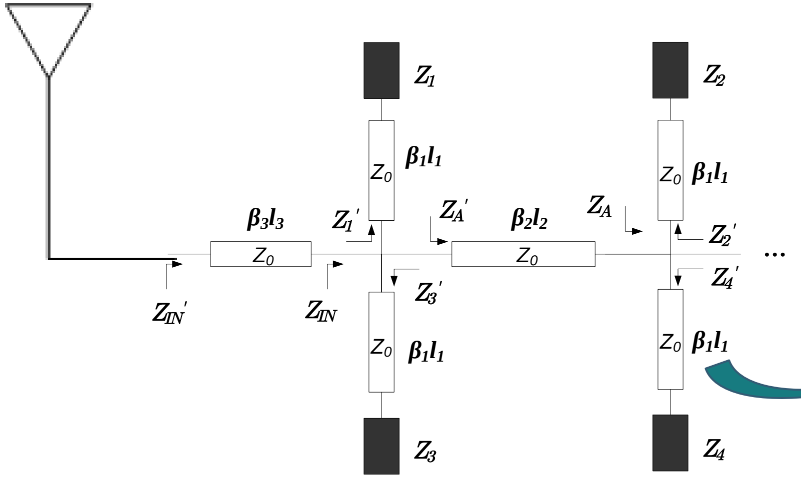
Multi-RFID scheme is implemented

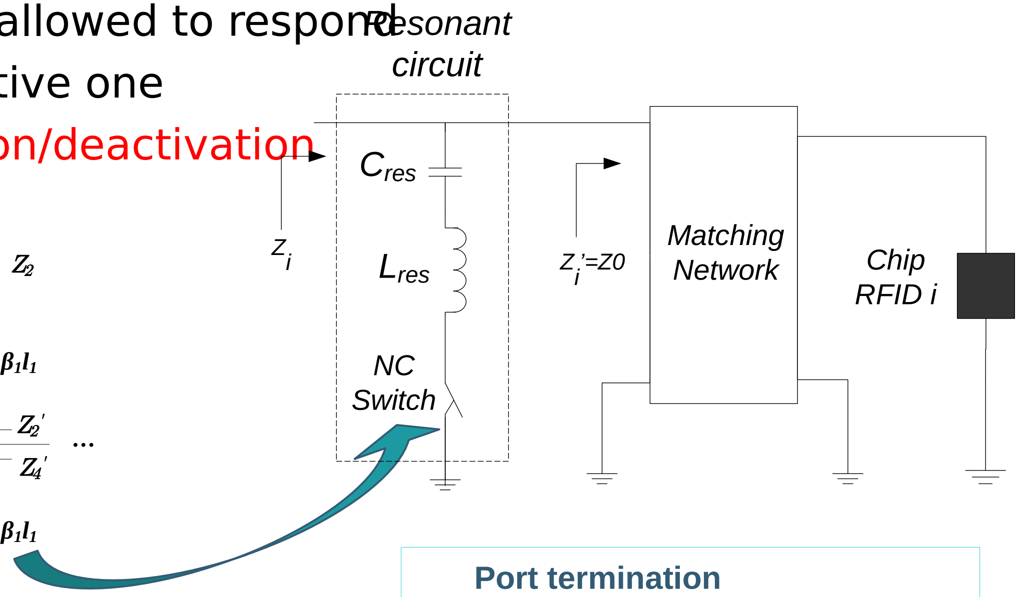
- Several RFID chips are used, each one associated to a key
- Only the chip associated to the pressed key should be read by the RFID reader to identify the key

MULTI-RFID SCHEME

Operating principle:

- N passive RFID tags associated to N keys/switchs
  - By default, no tag responds to reader (silent mode)
  - Once a key is pressed the respective tag is allowed to respond
  - Inactive tags must not interfere with the active one
- Two challenges: Antenna sharing, Tag activation/deactivation



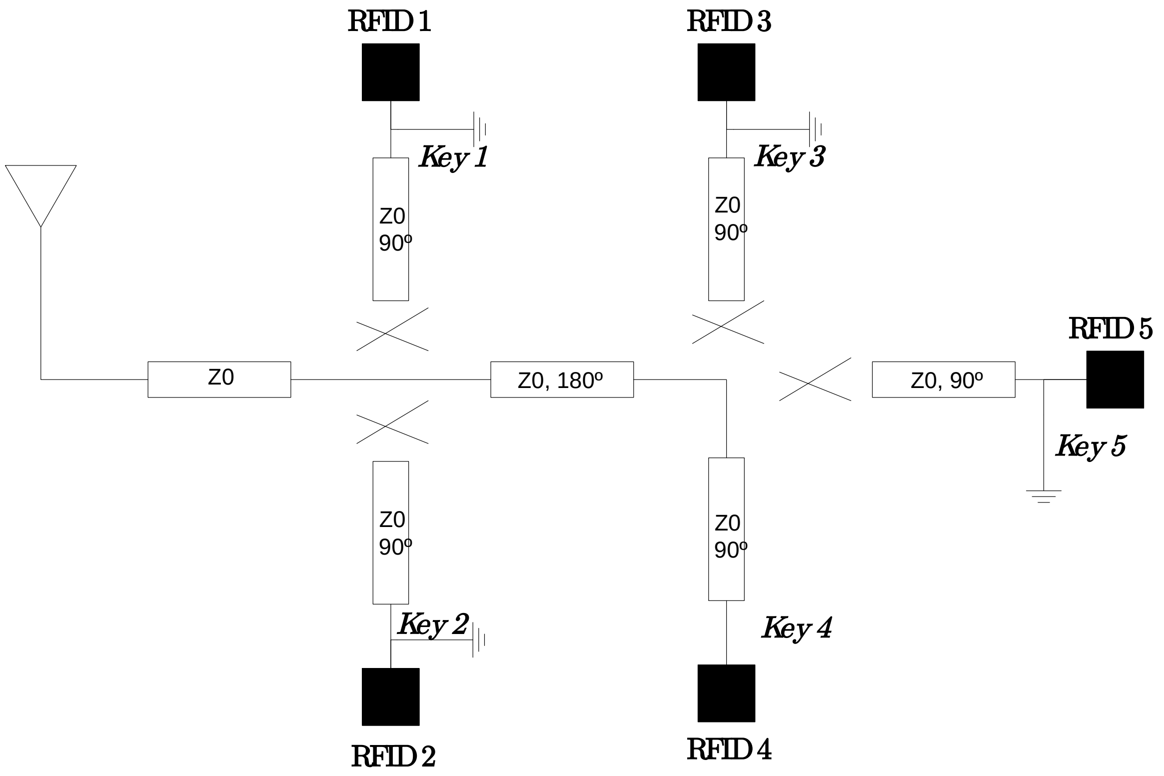


Port termination
= 0 Ohms by default
= 50 Ohms if user presses the key

Tags interconnection (N-port Network)

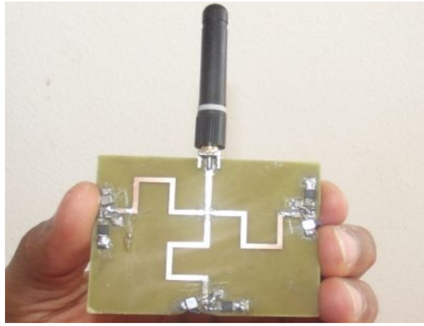
MULTI-RFID SCHEME

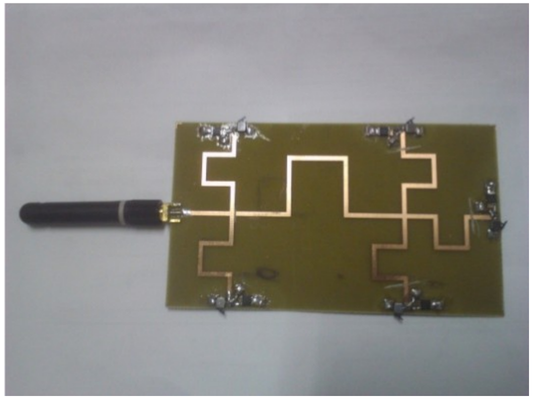
Example: key # 4 is pressed ✉ RFID4 is routed to the antenna port without interference of idle tags



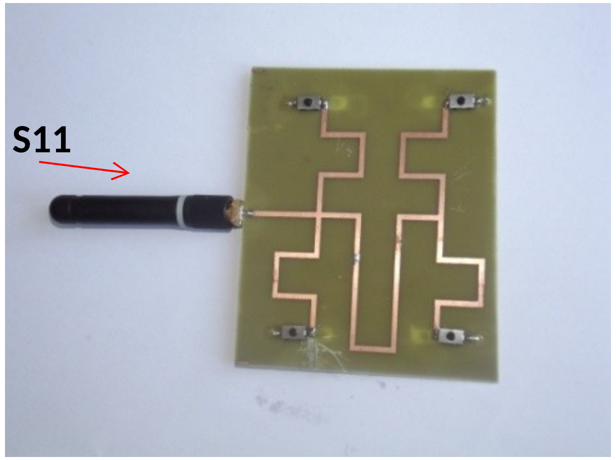
MULTI-RFID SCHEME - MEASUREMENTS

Remote control prototypes: 3, 4 and 5 keys

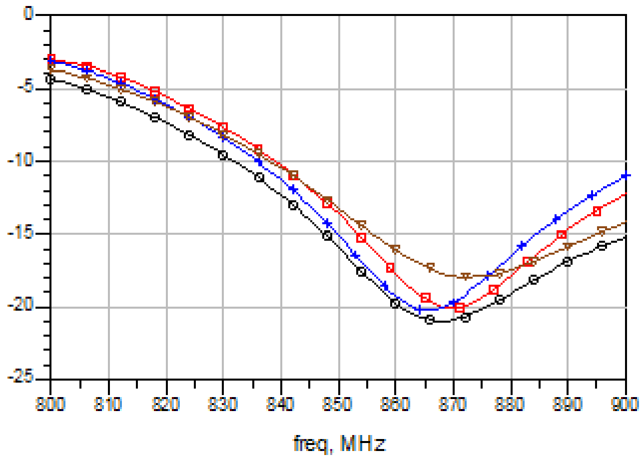




Return loss (S11) of 4-key prototype when each key is presses by the user



S11 - Return Loss (dB)

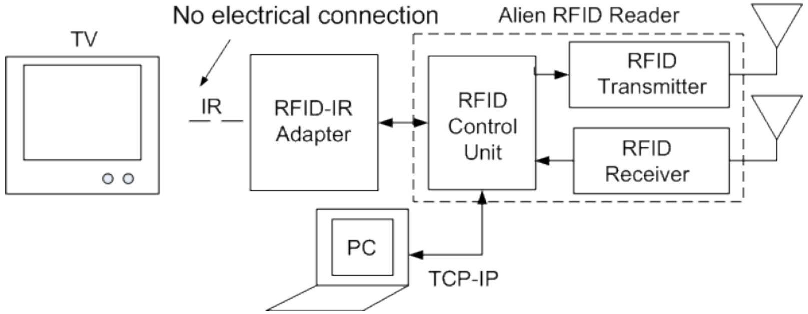


o – key 1 pressed
x – key 2 pressed
▪ – key 3 pressed
< – key 4 pressed

MULTI-RFID SCHEME

MEASUREMENTS

- ✓ The complete system has been successfully tested and val
- ✓ The remote control system has been integrated in a TV dev
- ✓ **CH +**, **CH -**, **Vol +** and **Vol –** functions were implemented



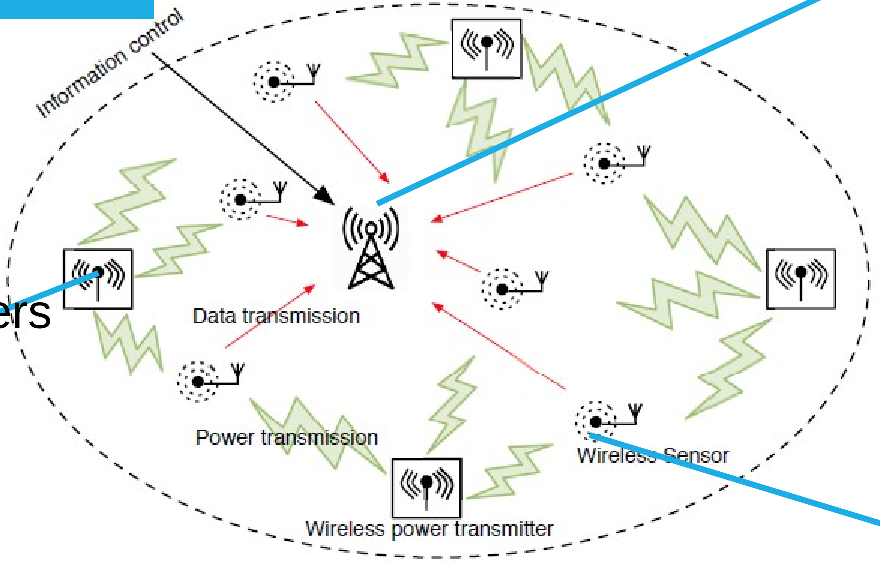
The prototype is composed by:

1) TV
2) RFID reader and Computer
3) RFID-IR adapter

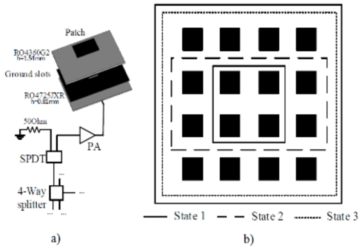
BATTERY-LESS WIRELESS NETWORK

Cloud RAN Access Point

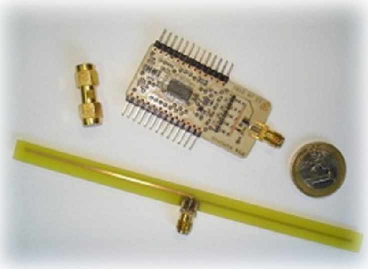
Real Implementation



Wireless Transmitters



Battery-less Sensors



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