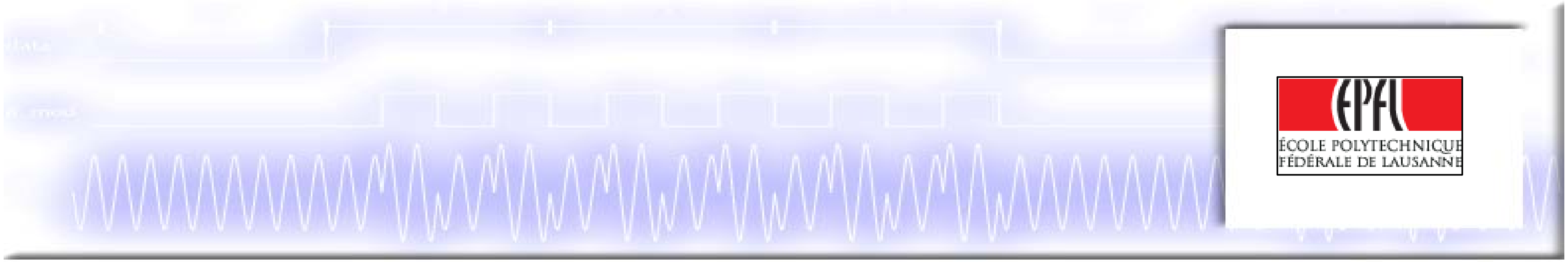

Design and Optimization of Passive UHF RFID Systems

Prof. Michel Declercq

Ecole Polytechnique Fédérale de Lausanne (EPFL)
Switzerland

michel.declercq@epfl.ch

OUTLINE

- Introduction
- Wireless Power Transmission
- Communication Issues
- Transponder (tag) and Reader Design
- Conclusion

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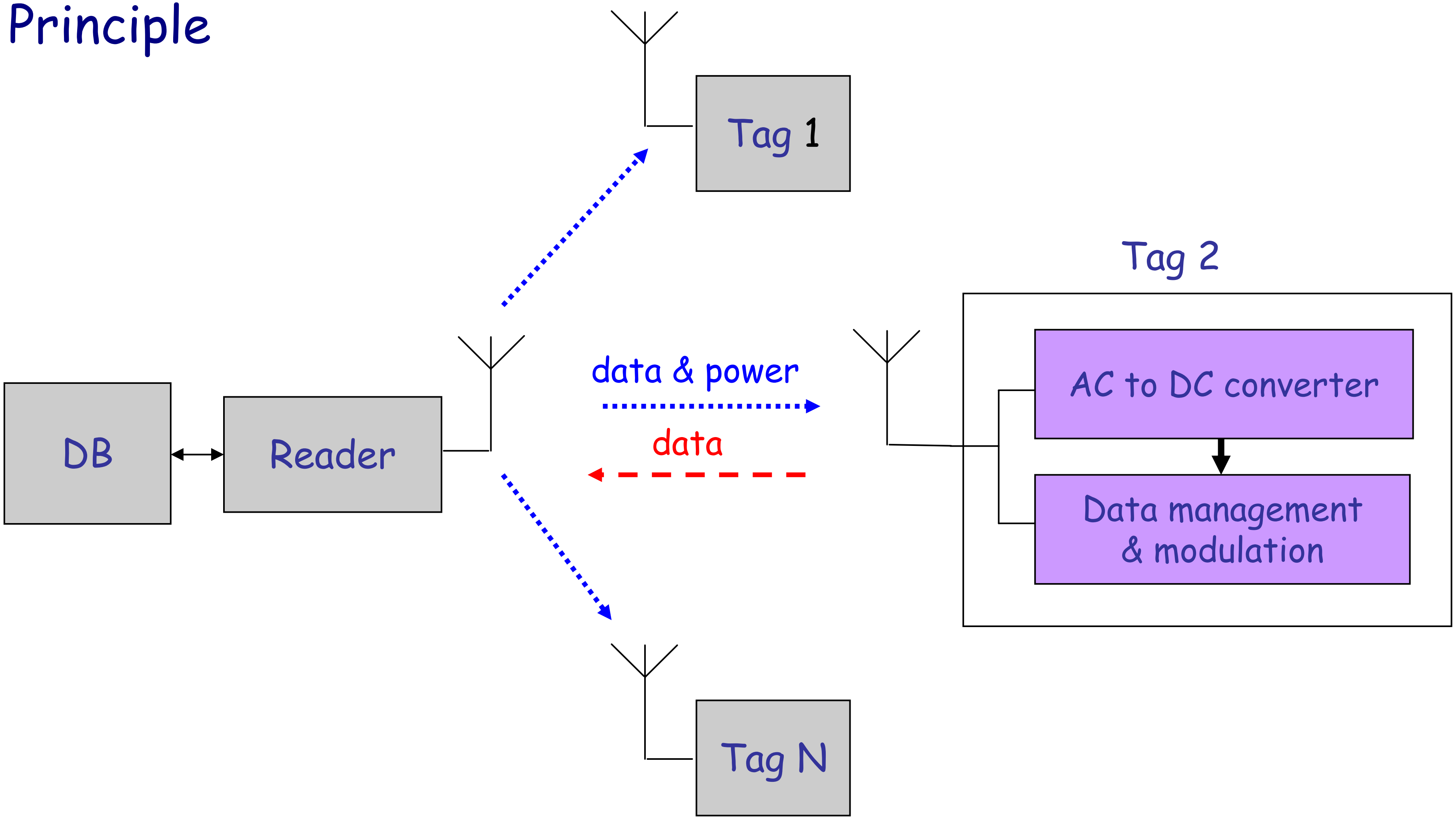
1. INTRODUCTION

Principle


Tag 1
Tag 2
DB
Reader
data & power
data
AC to DC converter
Data management & modulation
Tag N

Near-field (low frequency applications, up to 100 MHz)

- Starts in the direct neighborhood of any antenna up to d = $\frac{\lambda}{2\pi}$
- Usually inductive coupling (magnetic field)
- But can be capacitive coupling (electric field)
- Antennas have to be either coils for inductive coupling, or metallic surfaces for capacitive coupling
- Power decay in both cases is prop. to d^6

Far-field (high frequency applications, from 100 MHz)

- Far-field occurs at a distance of about $\frac{\lambda}{2\pi}$ from the antenna
- Electromagnetic coupling
- Antennas are typically of N-poles types (monopole, dipoles, etc.)
- Available Power varies with $\mathbf{d^{-2}}$ and λ^2.

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Wireless Power Transmission (WPT) in UHF passive systems

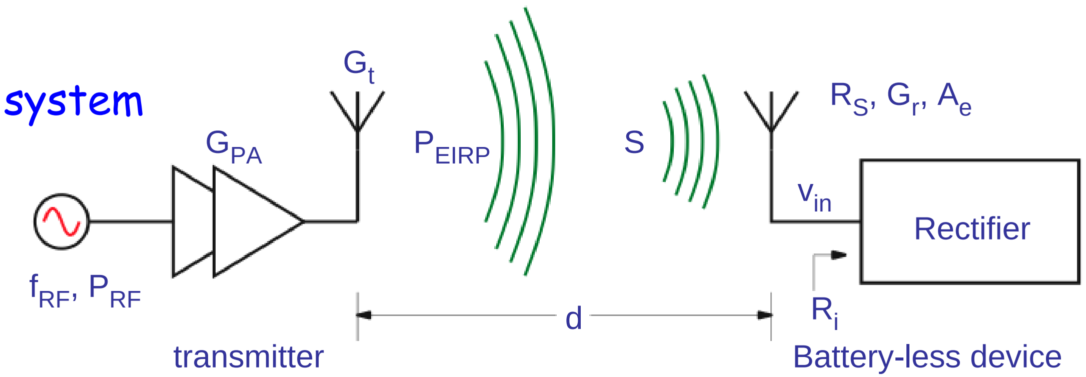
Some challenges:

- Power decay in the far-field is proportionnal to d^2
- Link budget is a function of d^{-4}
- RF to DC power conversion → Efficiency, Start-up voltage
- Tag and reader antenna design
- Type of Modulation for the backscattered signal
- Power management of tag circuits and signal encoding
- Reader design and sensitivity

Wireless Power Transmission (WPT) in UHF passive systems

A first estimation of power levels at tag (1/2):

Typical WPT system



- <u>Power density</u> at tag antenna: $S = P_{EIRP} \cdot \frac{1}{4\pi d^2}$
- Power collected by tag antenna and available to the load: $\boxed{P_{AV} = A_E . S}$

With <u>Antenna Aperture</u> $\boxed{A_E = \frac{\lambda^2}{4\pi} . G_R}$

Wireless Power Transmission (WPT) in UHF passive systems

A first estimation of power levels at tag (2/2):

$$\boxed{P_{AV} = S.\frac{\lambda^2}{4\pi}.G_R = P_{EIRP}.G_R.\frac{\lambda^2}{(4\pi d)^2}}$$

F_{RiiS} Relation

For

λ = 0,1224 m (2,45 Ghz)

P_{EIRP} = 4 W

G_R = 1 (0 dB): Antenna gain

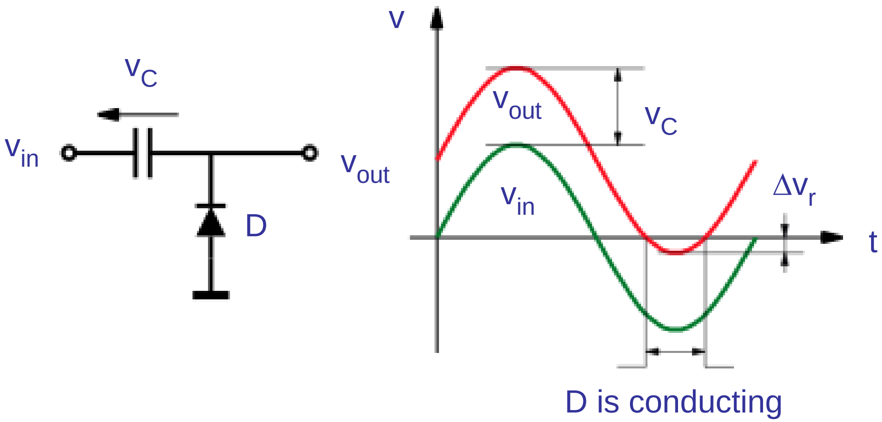
d(m)	P_{AV}(W)
1 m	379 μW
5 m	15.17 μW
10 m	3.79 μW
12 m	2.6 μW

2. Wireless Power Transmission

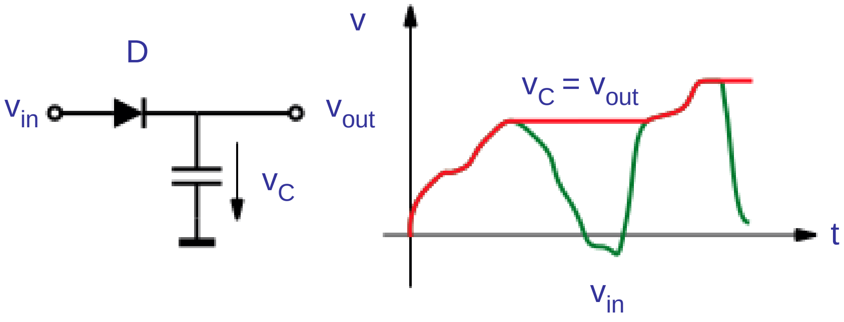
From low-voltage AC to high-voltage DC supply

Rectifier building blocks (*1/2*)

DC restorer



Peak detector



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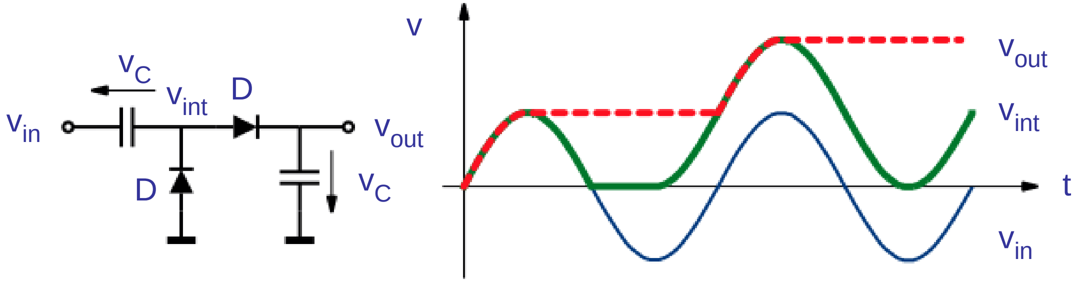
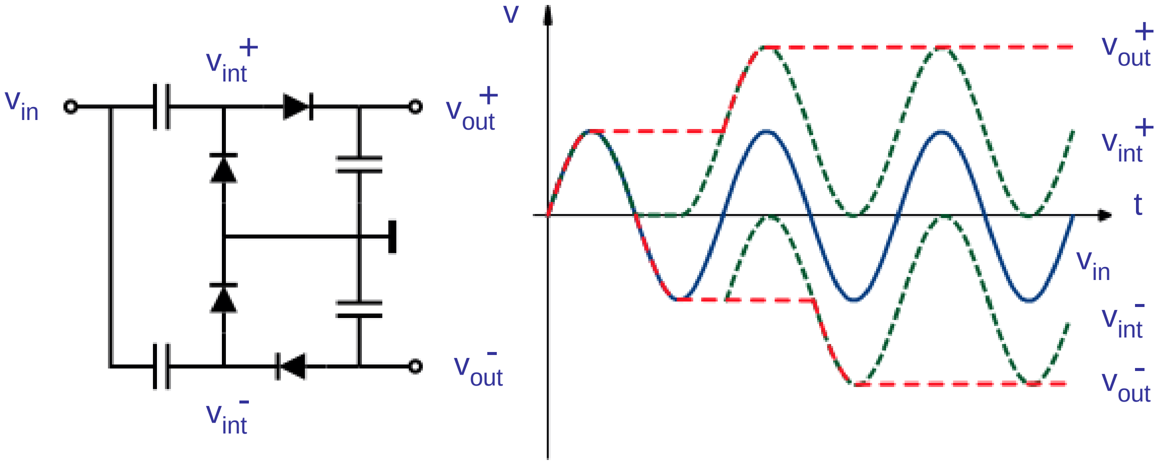
From low-voltage AC to high-voltage DC supply

Rectifier building blocks (*2/2*)

Voltage doubler



Full wave rectifier



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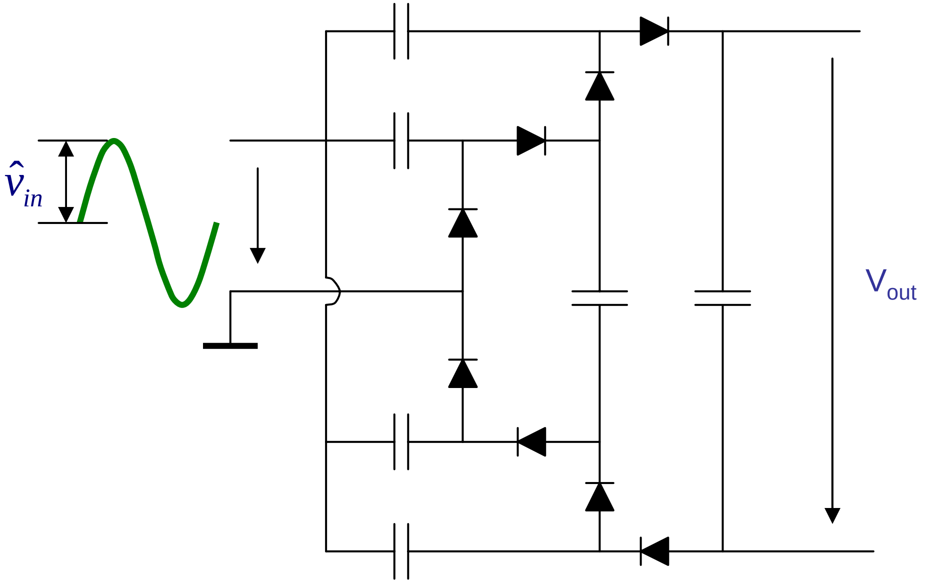
Rectifier Circuit (2 stage Greinacher)



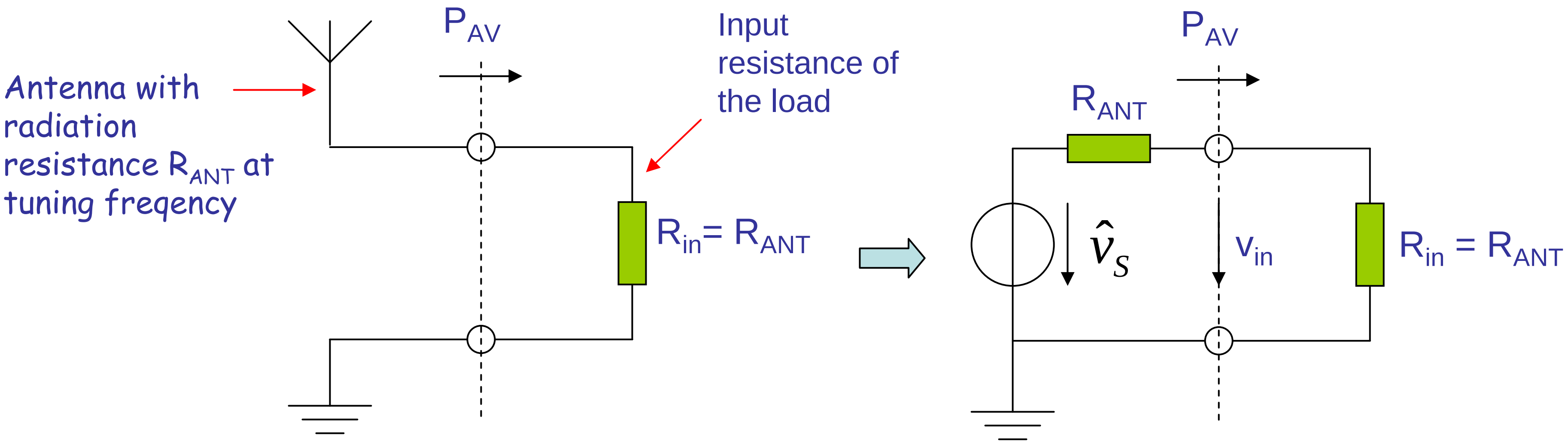
$$V_{out} = 4N\hat{v}_{in}$$

Where *N* is the number of stages

There is a need for a model taking into account

- The AC source v_{in} (antenna)
- The current delivered to the load
- Diodes non-idealities

Antenna Model



$$P_{AV} = \frac{\hat{v}_{in}^2}{2R_{in}} \rightarrow$$

At load matching conditions (R_{ANT} = R_{IN})

$$\boxed{\hat{v}_S = 2\hat{v}_{in} = 2\sqrt{2.P_{AV}.R_{ANT}}}$$

michel.declercq@epfl.ch

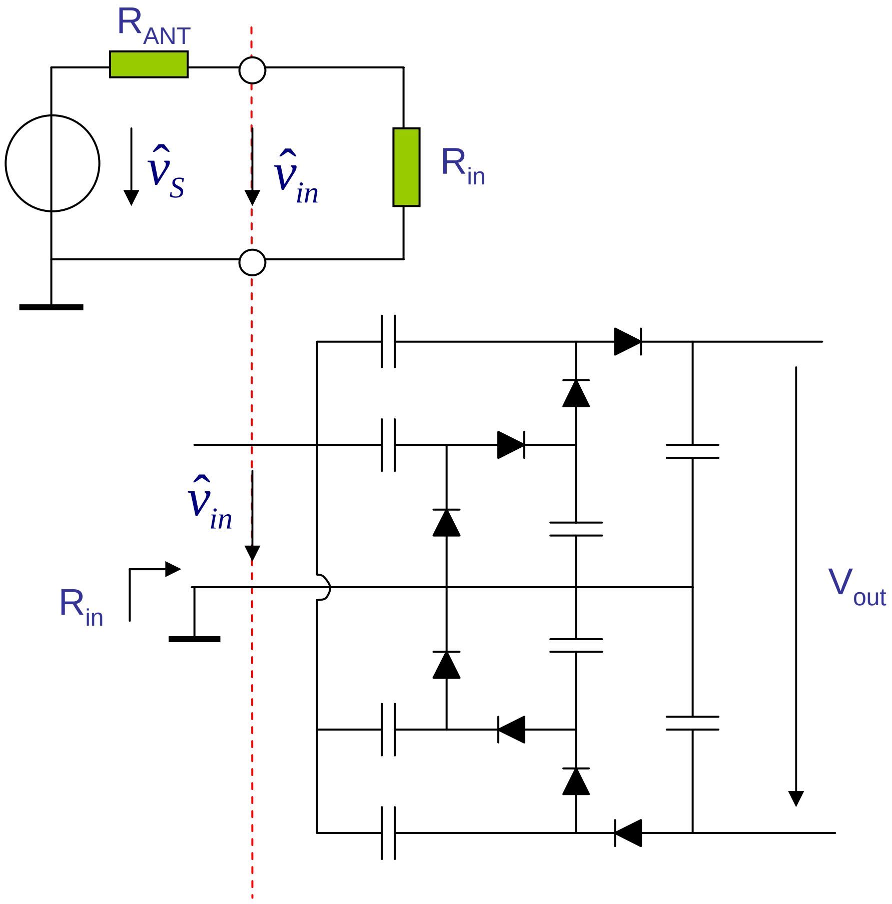
Rectifier input voltage: influence of R_{in}

The voltage amplitude $\hat{v}_{in}$ at the rectifier input is given by:

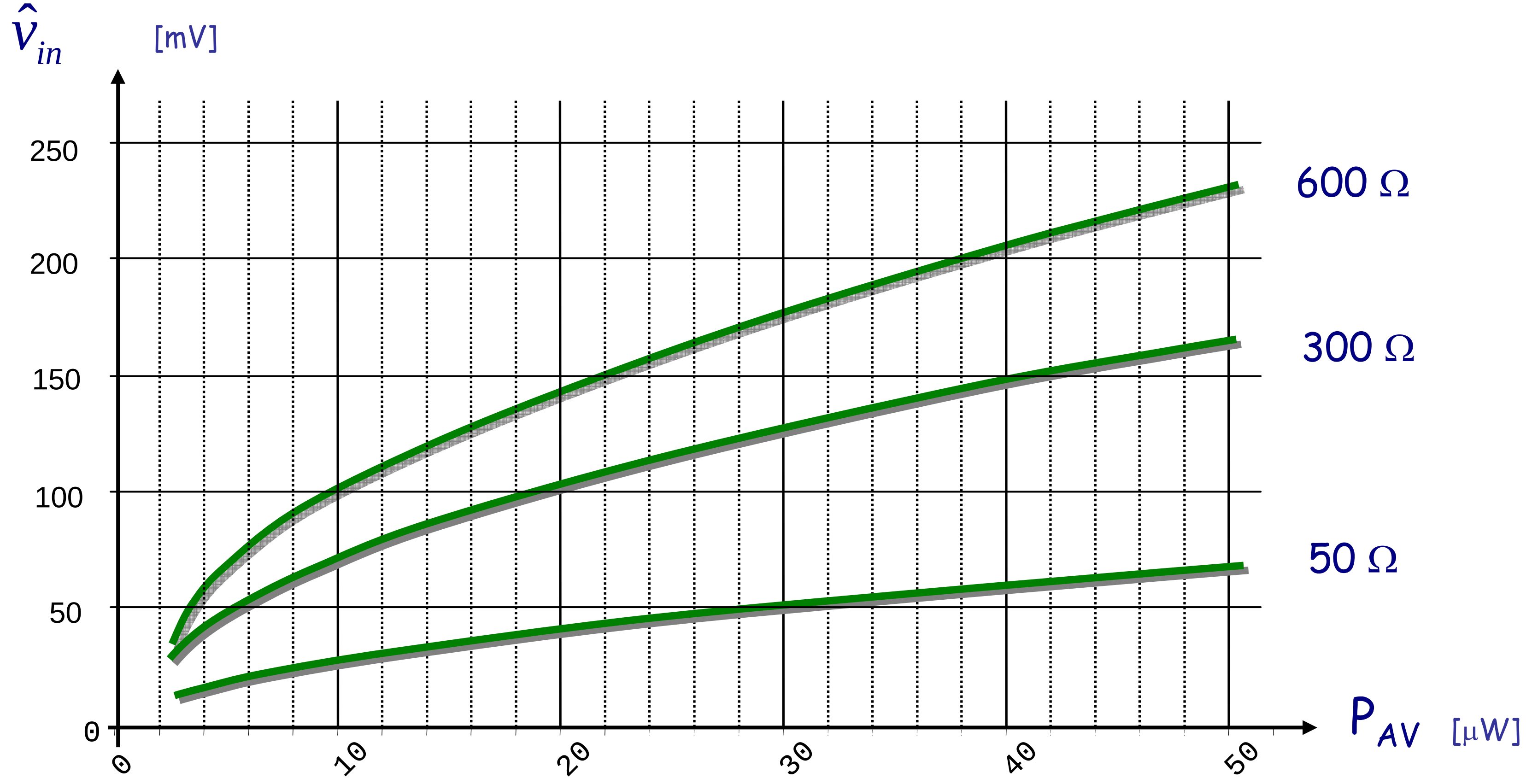
$$\hat{v}_{in} = 2\sqrt{2P_{AV}R_{ant}}\,\frac{R_{in}}{R_{in}+R_{ant}}$$

To maximize $\hat{v}_{in}$ and Power:

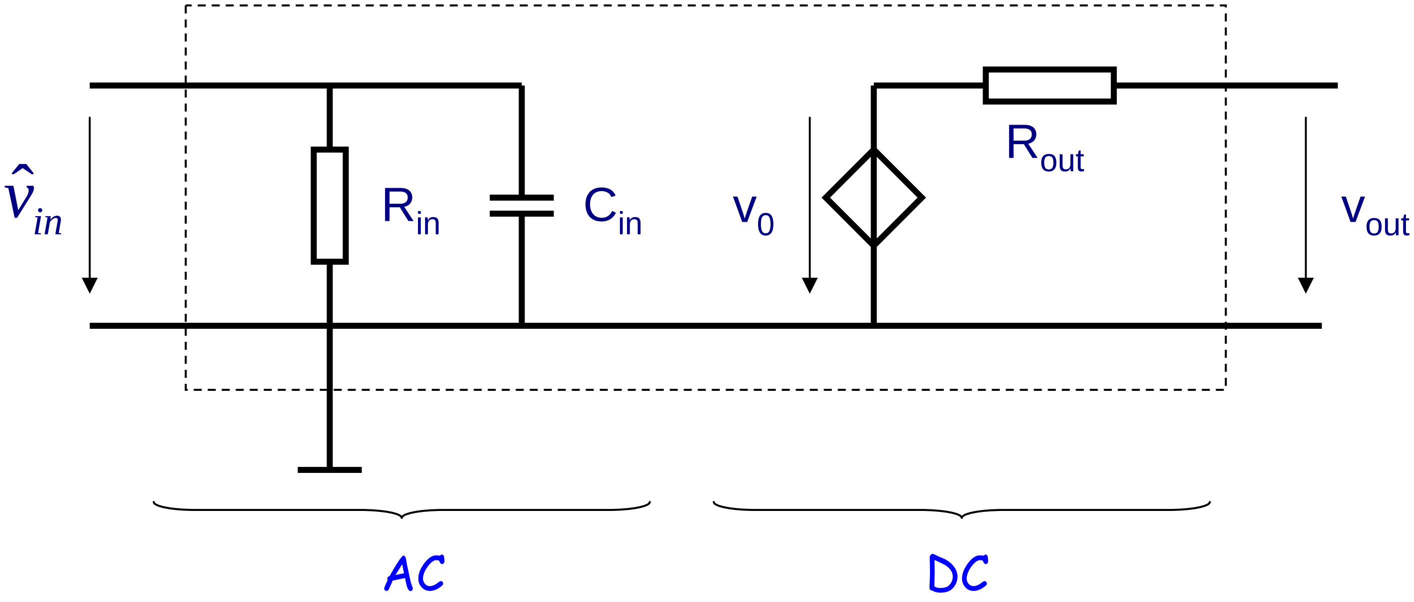
- Maximize R_{ant}
- Keep R_{in} equal to R_{ant}



Rectifier input voltage for $R_{ANT} = R_{in}$



Rectifier Equivalent Circuit Model



Assumptions

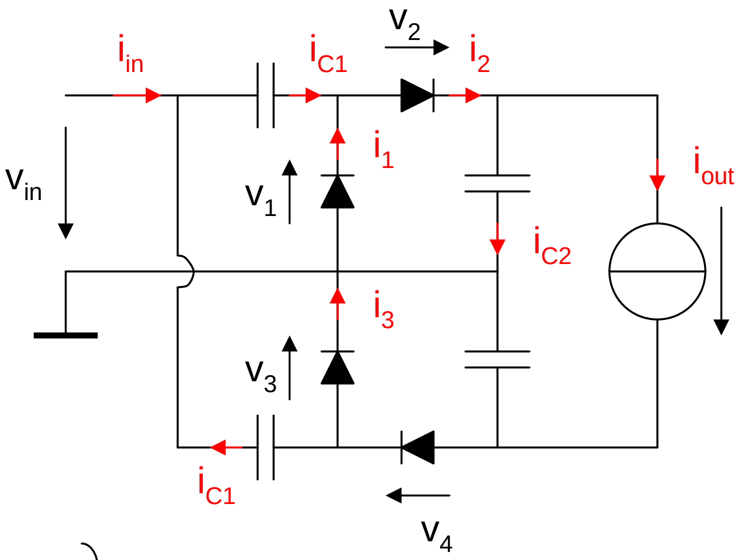
- The rectifier operates in steady-state mode;
- The ouptut current is constant;
- All diodes are identical;
- The coupling capacitors are considered as short-circuits at the RF frequency
- The rectifier input current is transformed into an equivalent sinusoïdal current

Model Derivation (steady state conditions)

1. Ideal diodes

$$\int_0^T i_C(t)dt = 0$$ For all capacitors

$$\Rightarrow \int_0^T i_D(t)dt = I_{out}.T$$ For all diodes



$$v_{out} = 4N.\hat{v}_{in}$$

$$\overline{P_{in}} = \frac{1}{T}.\int_0^T v_{in}(t).i_{in}(t)dt = \frac{\hat{v}_{in}^2}{2.R_{in}}$$

also

$$\overline{P_{in}} = P_{out,DC} = V_{out}.i_{out} = 4N.\hat{v}_{in}.i_{out}$$

$$\Rightarrow \boxed{R_{in} = \frac{\hat{v}_{in}}{8NI_{out}}}$$

Model Derivation (steady state conditions)

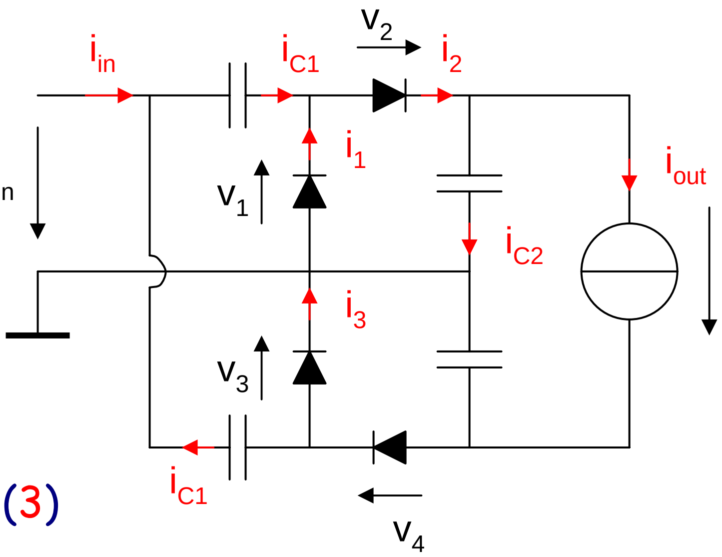
2. Real diodes

$$\int_0^T i_C(t)dt = 0$$ For all capacitors (1)

$$\Rightarrow \int_0^T i_D(t)dt = I_{out}.T$$ For all diodes (2)

with $i_D(t) = F[v_D(t)]$ Real diode characteristic (3)

and $v_D(t) = \overline{V_D} \pm \hat{v}_{in}.\sin\omega t$ (4)



$$v_{out} = 4N.\overline{V_D}$$

with

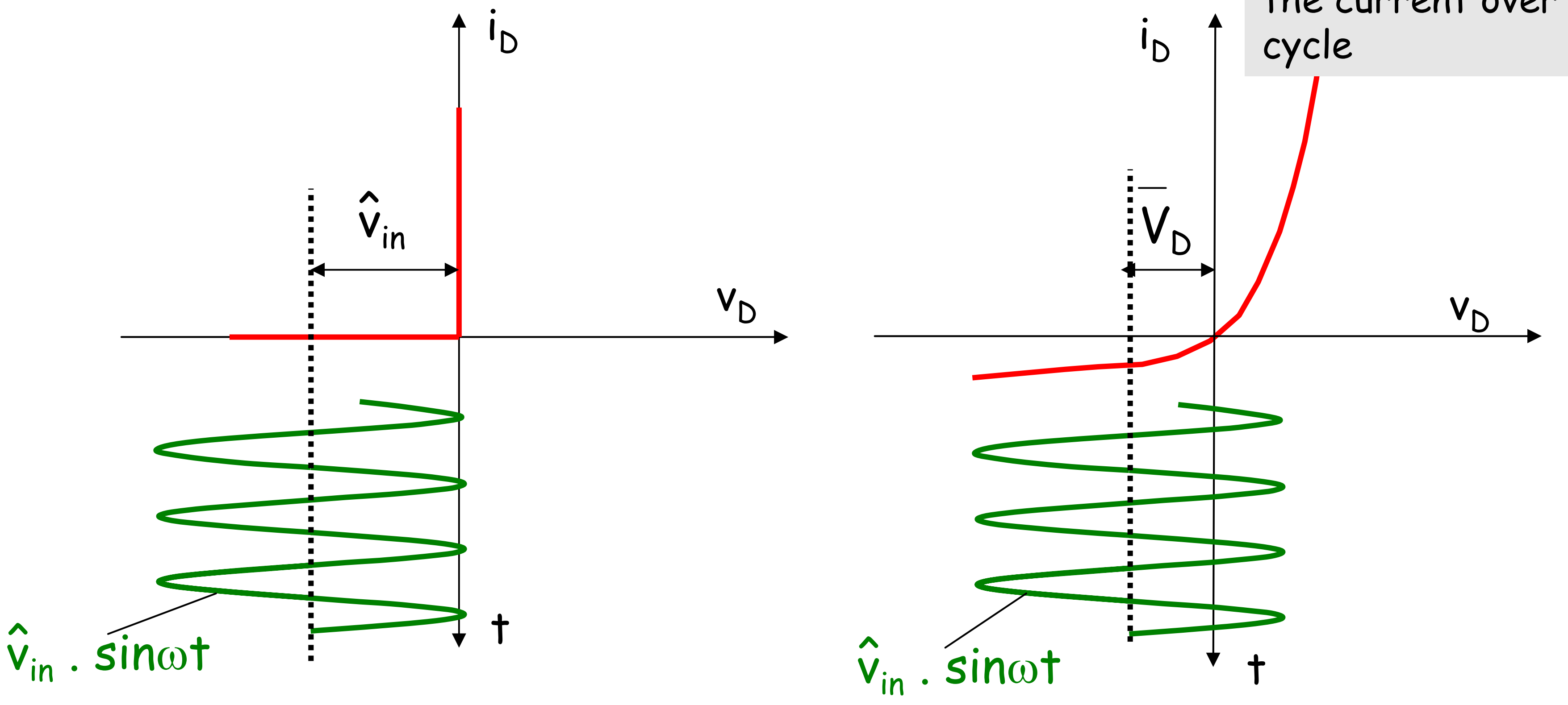
$$\overline{V_D} < \hat{v}_{in}$$

- V_D is obtained by solving (1), (2), (3)
- It can be shown that $\boxed{v_{out} = 4N.\overline{V_D}}$

Model Derivation (detail)

Ideal Diodes vs. Real Diodes

With real diodes, V_D must be lower than $\hat{v}_{in}$ to get a positive balance of the current over one cycle



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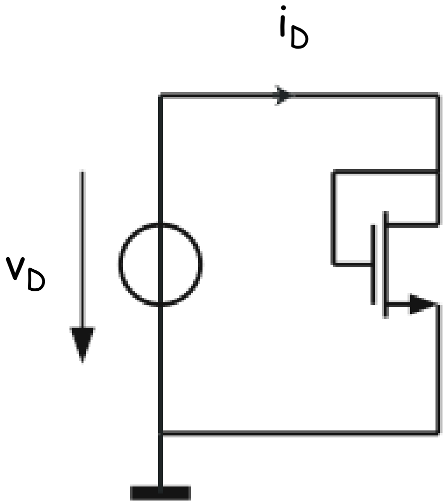
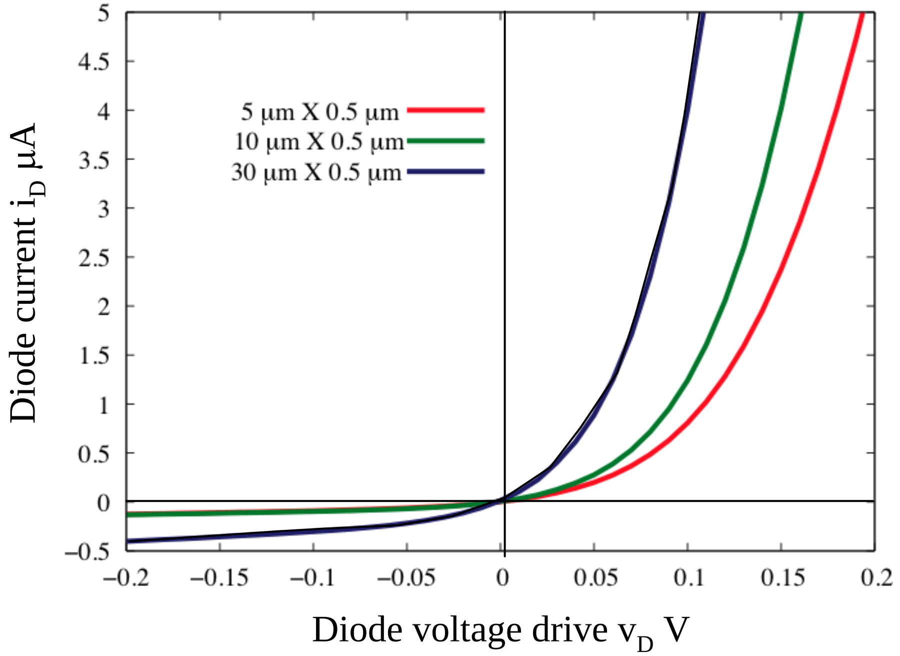
Current/Voltage characteristics of MOS diodes



Diode mounted transistor

Current-voltage characteristics of typical measured device



Determination of R_{in} (Real diodes)

- R_{in} models the power that enters the circuit:

$$P_{in} = \frac{1}{T}\int_0^T v_{in} i_{in}(t)\,dt = \frac{4N}{T}\int_0^T v_{in} i_D(t)\,dt$$

- The mean power can also be calculated using the usual relation:

$$P_{in} = \frac{\hat{v}_{in}^2}{2R_{in}} \qquad \boxed{\Rightarrow R_{in} = \frac{\hat{v}_{in}^2}{\frac{8N}{T}\int_0^T v_{in} i_D(t)\,dt}}$$

- Based on the I/V characteristic of a *single diode*, we can compute the power-equivalent input resistance R_{in}

michel.declercq@epfl.ch

Determination of C_{in}

- Our approach to calculate C_{in} is to compute the mean capacitance over one period of time:

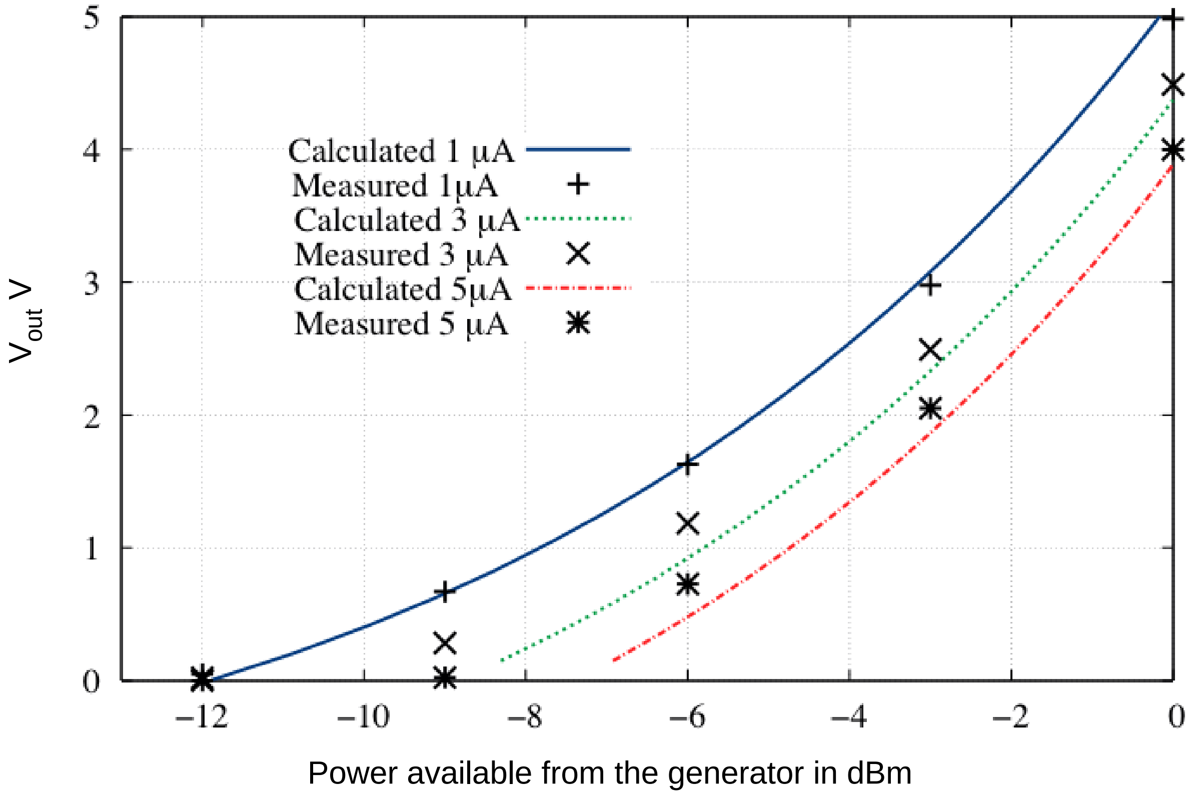
$$\boxed{C_{in} = \frac{4N}{T}\int_0^T C_D\left[\overline{V_D} + \hat{v}_{in}\sin\omega t\right]dt}$$

where $\overline{V_D}$ is the constant voltage that appears on each diode during steady-state

- Based on the C/V characteristic of a *single diode*, we can compute the equivalent input capacitance C_{in}

Measurements & Comparisons

Output voltage vs Input Power (50Ω, 900 MHz), 0.5µm SOS Techno



Model possibilities

The model allows a reasonably accurate prediction of:

- The output voltage (V_0)
- The input impedance (R_{in}, C_{in})
- The output resistance
- The conversion efficiency

as a function of:

- The DC output Power / Current
- The antenna radiation resistance (R_{ant})
- The available power P_{AV} at the antenna
- The characteristics of the MOS diodes

michel.declercq@epfl.ch

3. COMMUNICATION ISSUES

Modulation Types

The reflection coefficient at the tag-antenna interface can be varied in:

- Amplitude
- Phase

Two basic binary modulation types are possible: ASK & PSK

They must be compared in terms of

- Power available for both tag supply & for communication
- Communication quality (Bit Error Rate BER)

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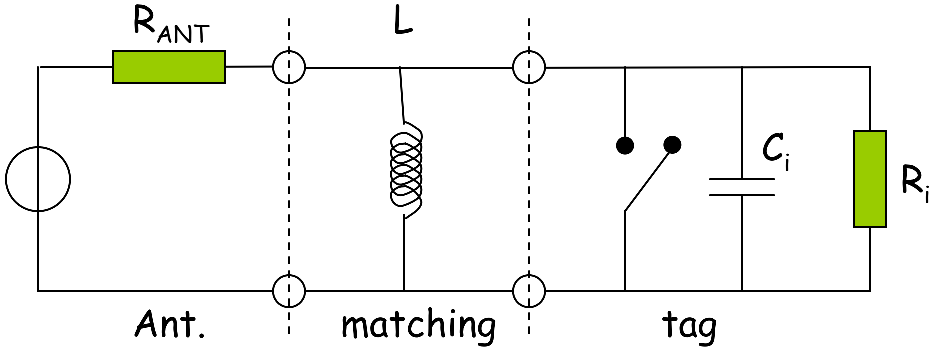
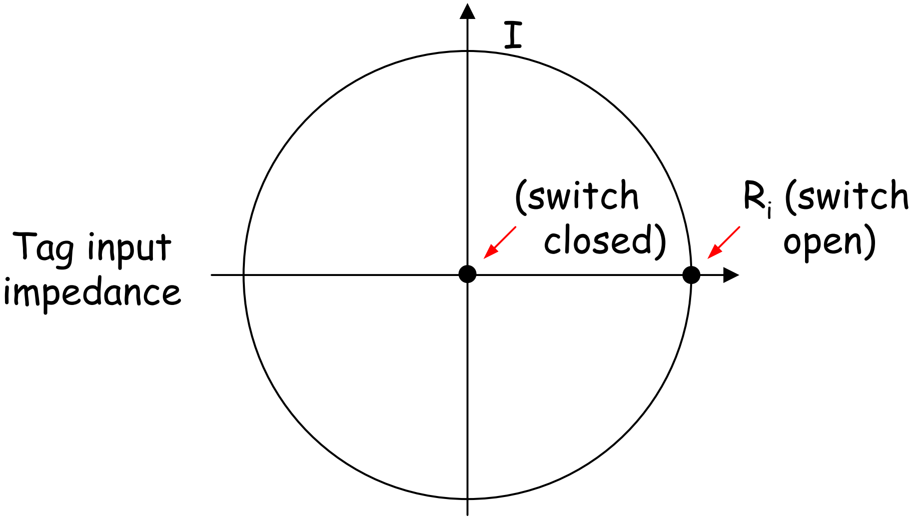
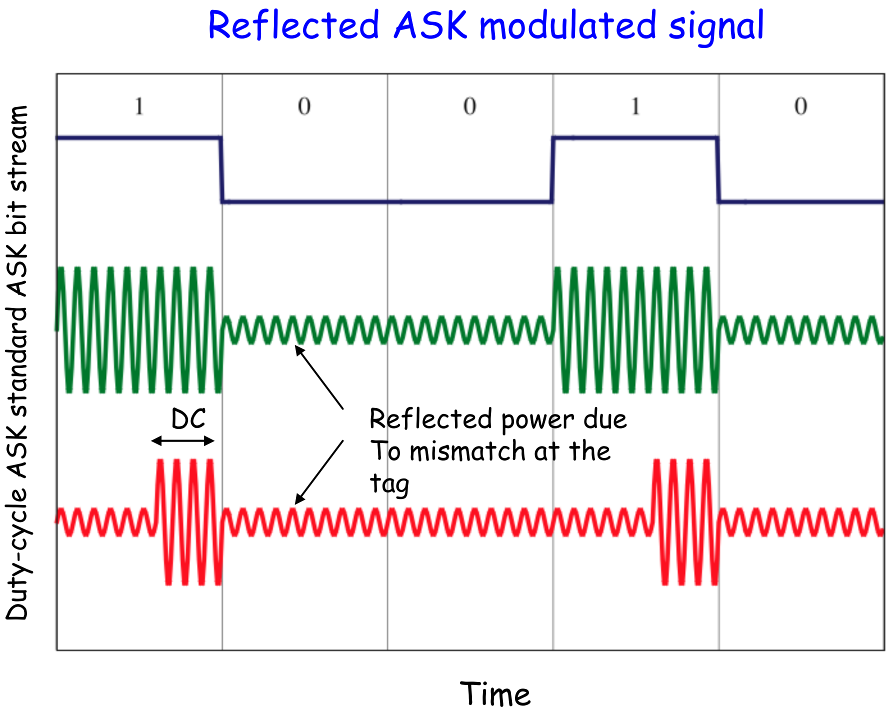
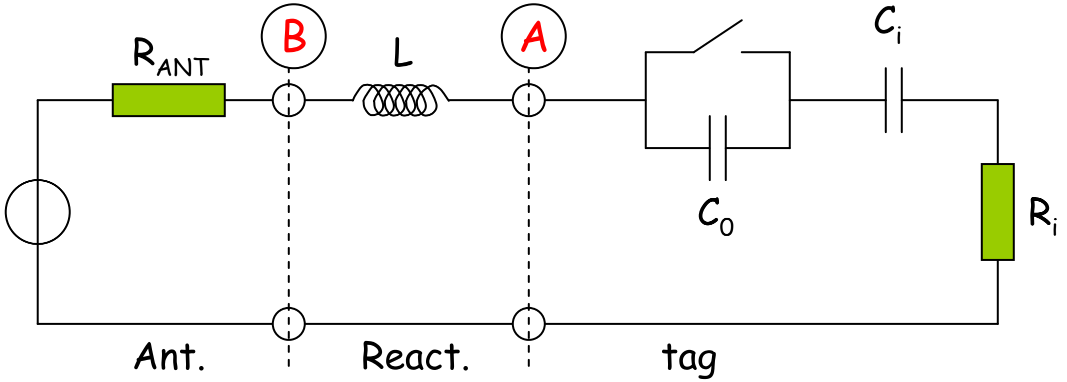
ASK modulation





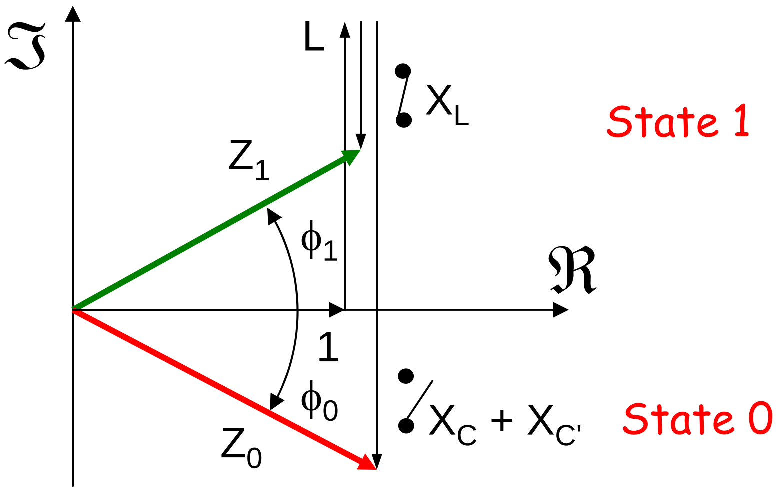


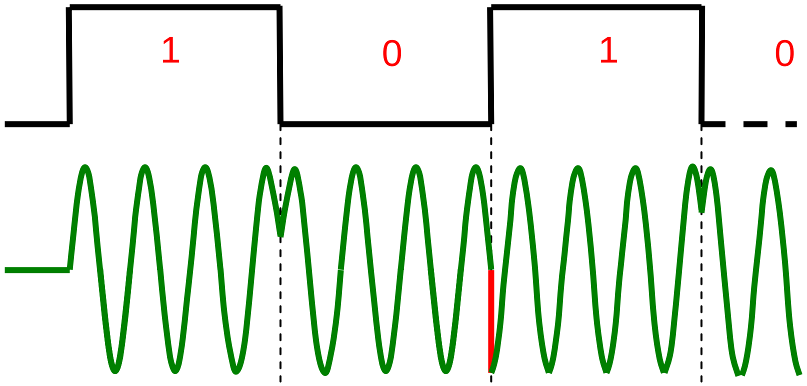
PSK modulation



In B: Absorbed power
And reflected power
are constant

In A: Voltage at tag input
is however not constant





Tag input impedance at **B**

ASK / PSK Comparison

E_b = Average Energy per bit
N_0 = Noise level at receiver input
α = R_i / R_{ANT}
Q = tag input series Quality factor $1/\omega.R_i.C_i$
DC = Modulation Duty Cycle

ASK

$$BER = Q\left(\sqrt{\frac{E_b}{N_0}.DC.\left(-1+\sqrt{\frac{\left(Q_{in}^2+1\right).(\alpha-1)^2}{(\alpha+1)^2+Q_{in}^2(\alpha-1)^2}}\right)^2}\right)$$

PSK

$$BER = Q\left(\sqrt{2\frac{E_b}{N_0}.\frac{4+\alpha\left(-8+\alpha\left(4+Q_{in}^2\right)\right)}{4+\alpha\left(8+\alpha\left(4+Q_{in}^2\right)\right)}.\sin\left(2\arctan\left(\frac{4Q_{in}\alpha}{-4+\alpha^2\left(4+Q_{in}^2\right)}\right)\right)^2}\right)$$

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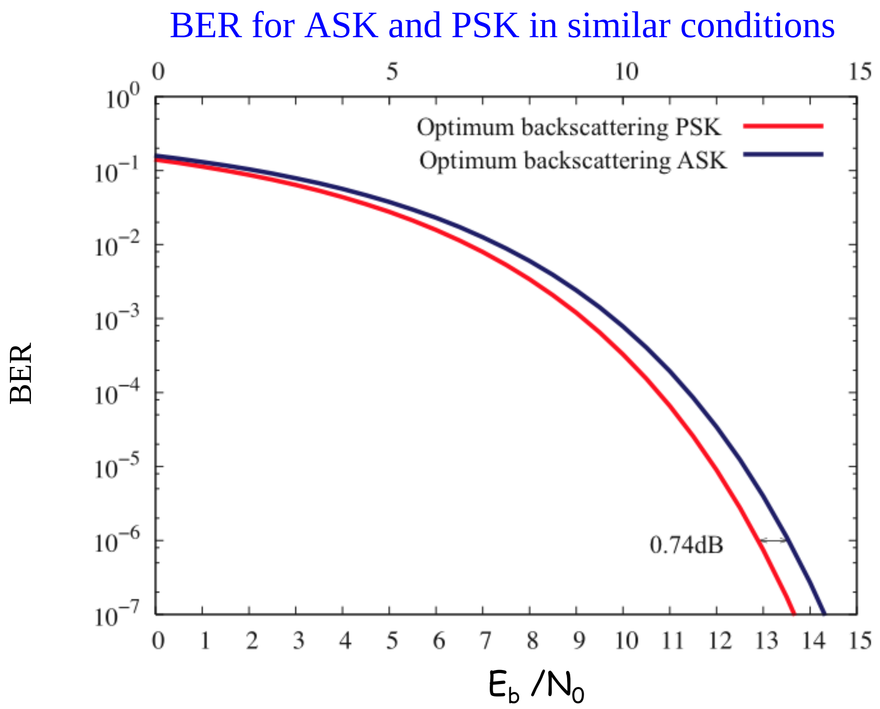
ASK / PSK Comparison



Optimal ASK and PSK BER comparison
(ASK: DC = 100%, α = 1 and PSK: α = 1, Qin = 5.6)

Tag input impedance for long-distance RFID

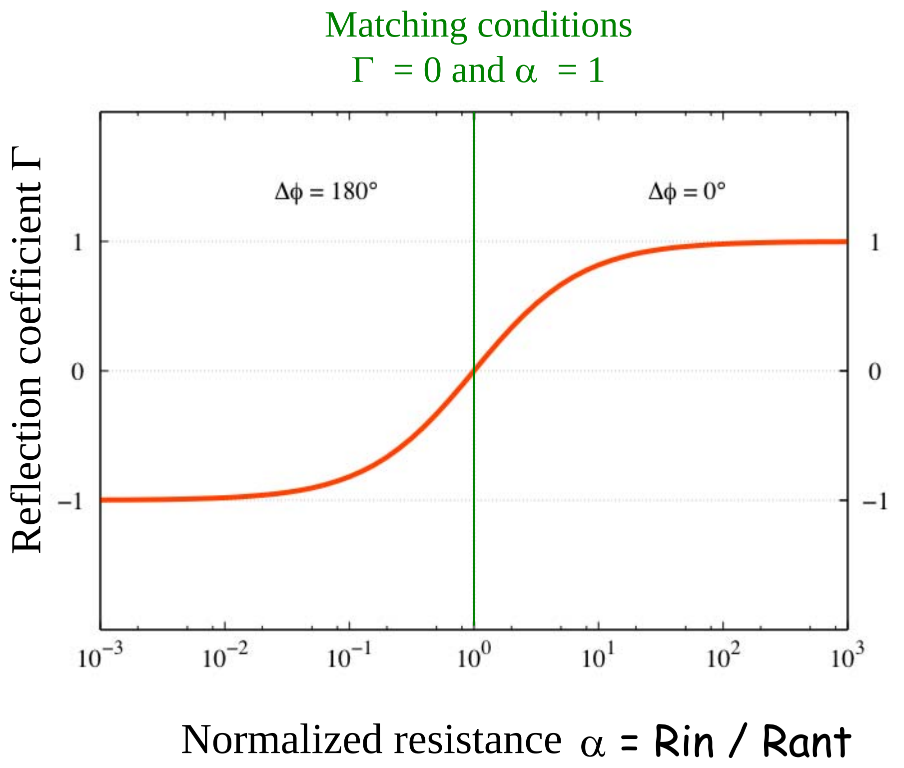
Priority is given to communication distance vs. data rate

The real part of R_{in} is very high (»1kΩ) and much higher than R_{ant}

Reflection coefficient is close to ±1

The input capacitance is equal to a few hundreds fF

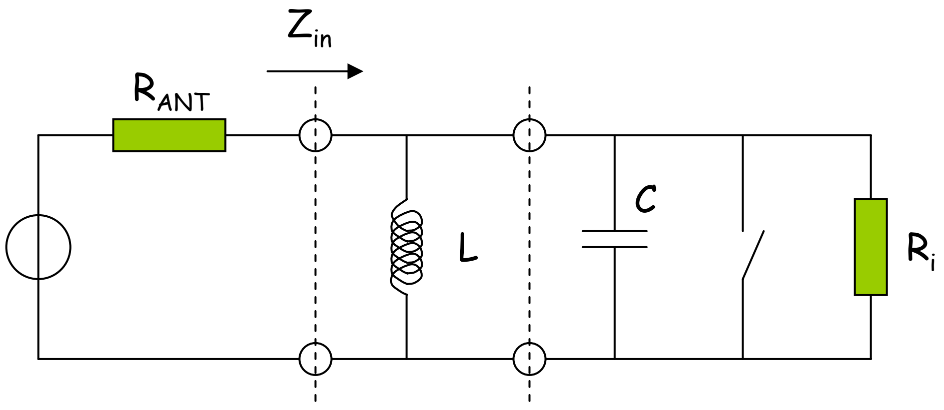
Reflection coefficient amplitude

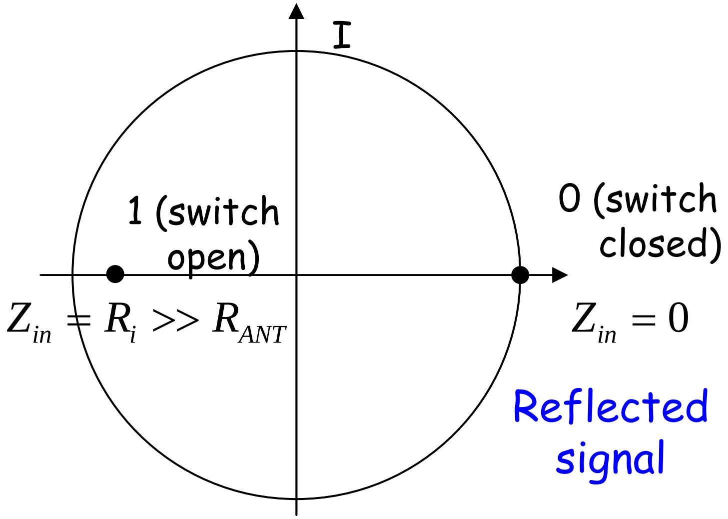


Pseudo - PSK

In practice $R_i > R_{ANT}$ (~1 order of magnitude)

- Absorbed power is lower than ideal
- Voltage available at rectifier input is higher
- Modulation is very efficient with a 180° phase shift

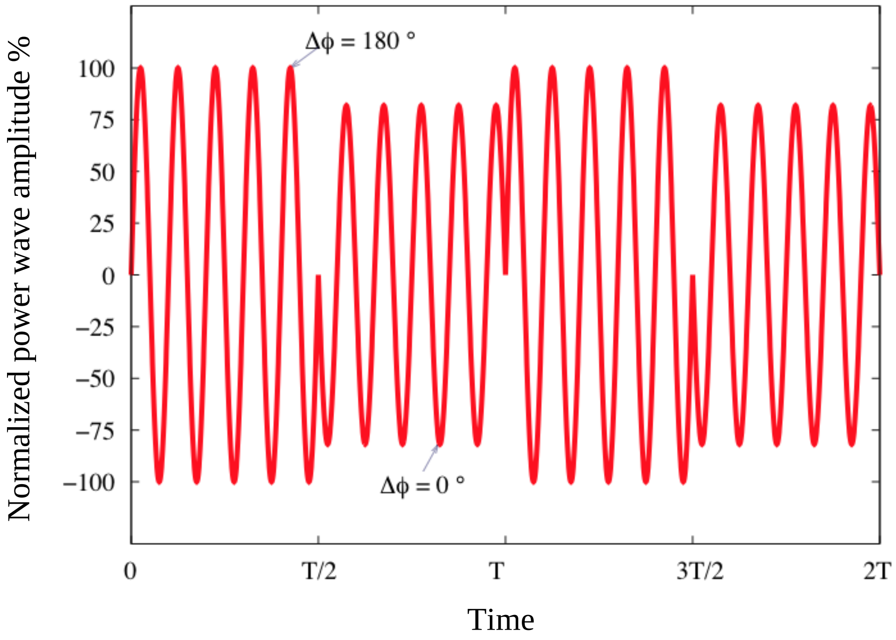




Reflected signal

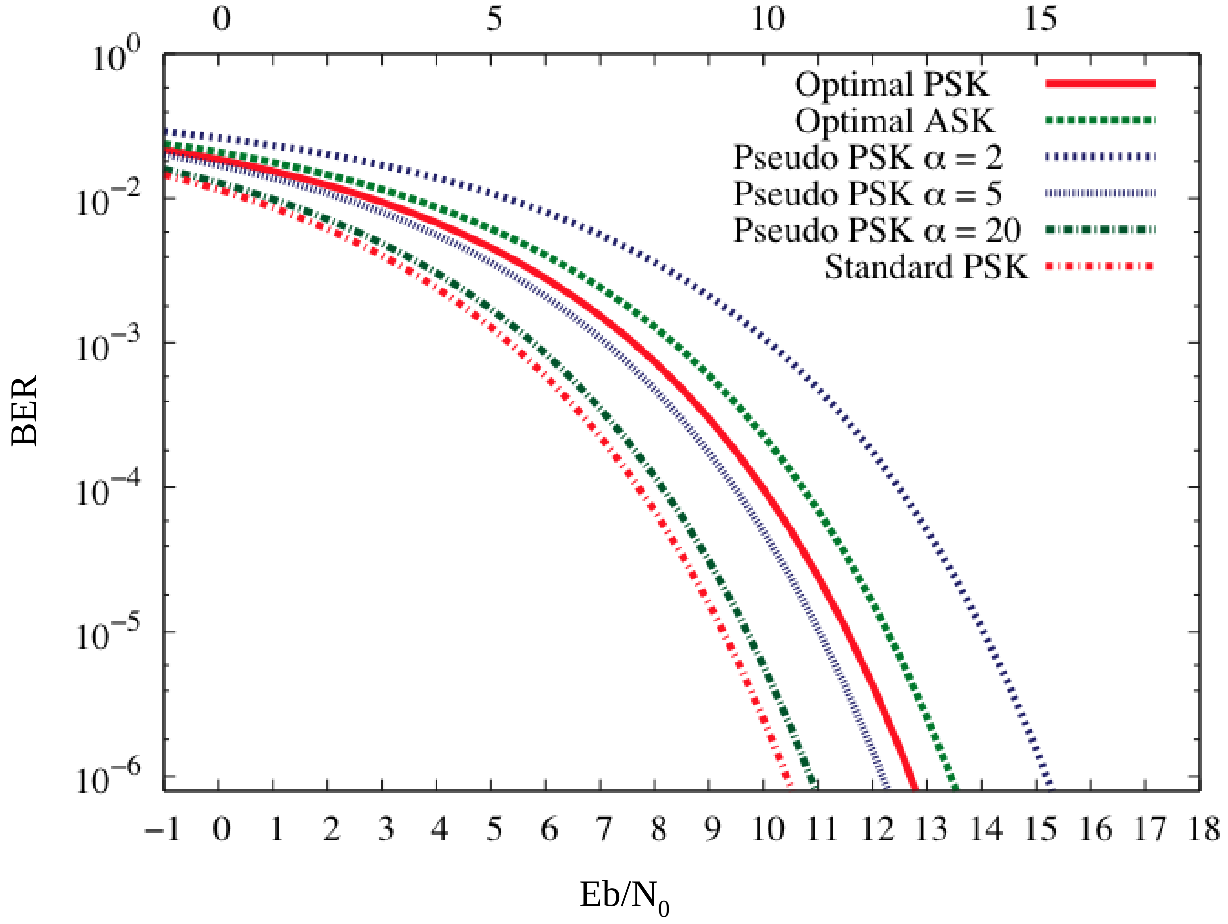
Power waves

Power waves for both modulation states



Modulation Type Comparison

ASK, PSK & pPSK comparison



Pseudo-PSK is an excellent trade-off considering the high impedance level of the tag RF front-end in this application

4. TAG AND READER DESIGN

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Initial Specifications for the tag IC

Parameter	Value
Frequency range	2.40 - 2.48 Ghz
Reader P_{EIRP}	4 W
Tag power	$\approx 1\ \mu W$
Operating distance	> 5 m
Reader to tag	AM (OOK) modulation
Tag to reader	p-PSK modulation
Data rate	$\geq$ 10 kbps

michel.declercq@epfl.ch

Technological Issues

Desired features

- Low-V_T rectifying devices ➔ start-up voltage
- Steep subthreshold slope ➔ efficiency
- Overall excellent RF behaviour ➔ µwave operation

Selected technology

PEREGRINE 0.5µm FD SOS Technology
Gate oxide thickness : 10 nm
Silicon layer thickness : 100 nm
3 V_T's available for both N-channel & P-channel transistors
F_T,typ = 14 Ghz, F_{MAX},typ = 55 Ghz @ V_{DS}=1.5V & I_D=5mA (n-chan.)

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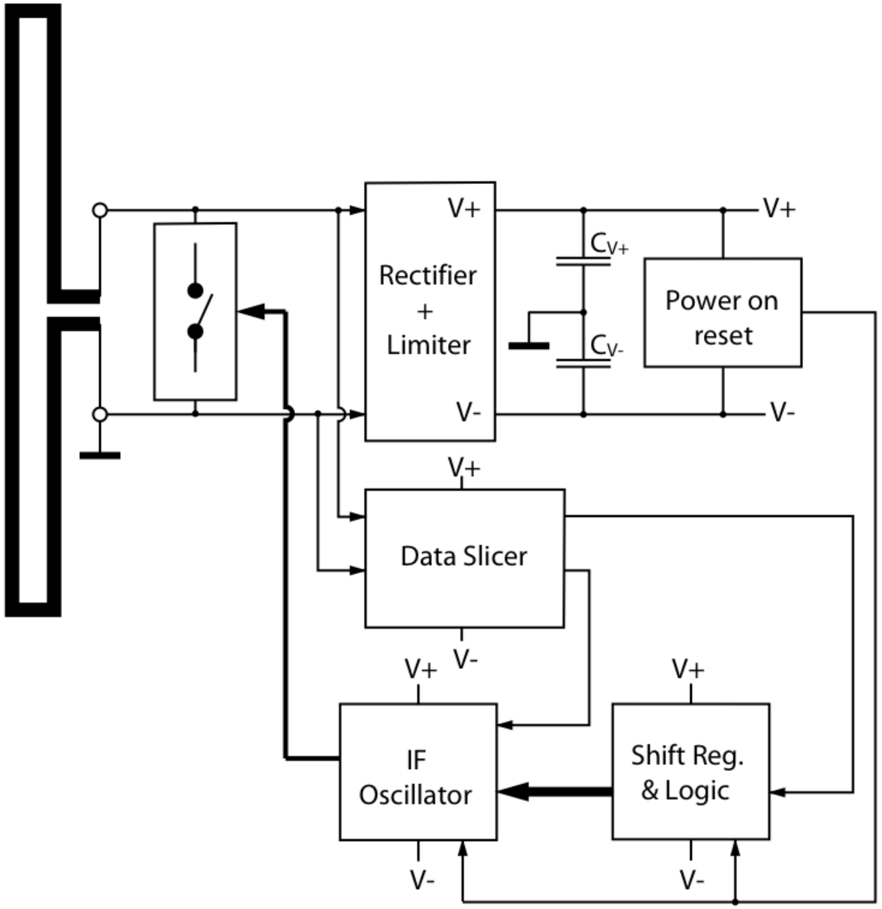
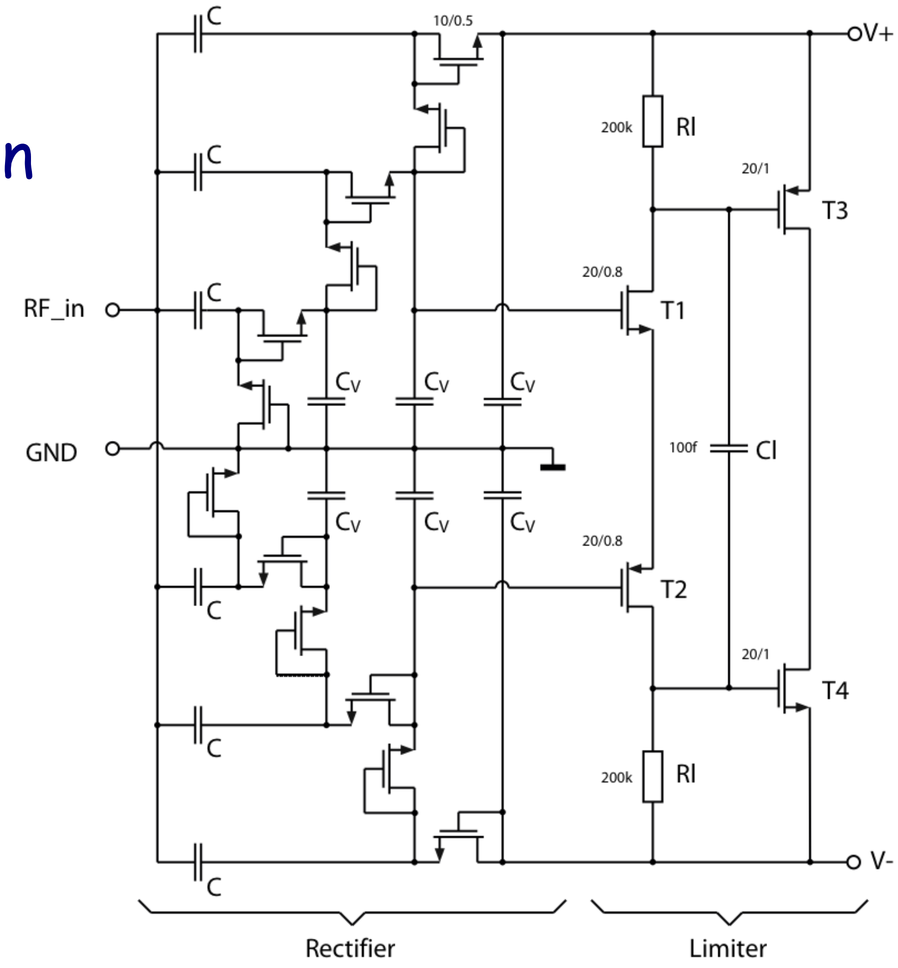
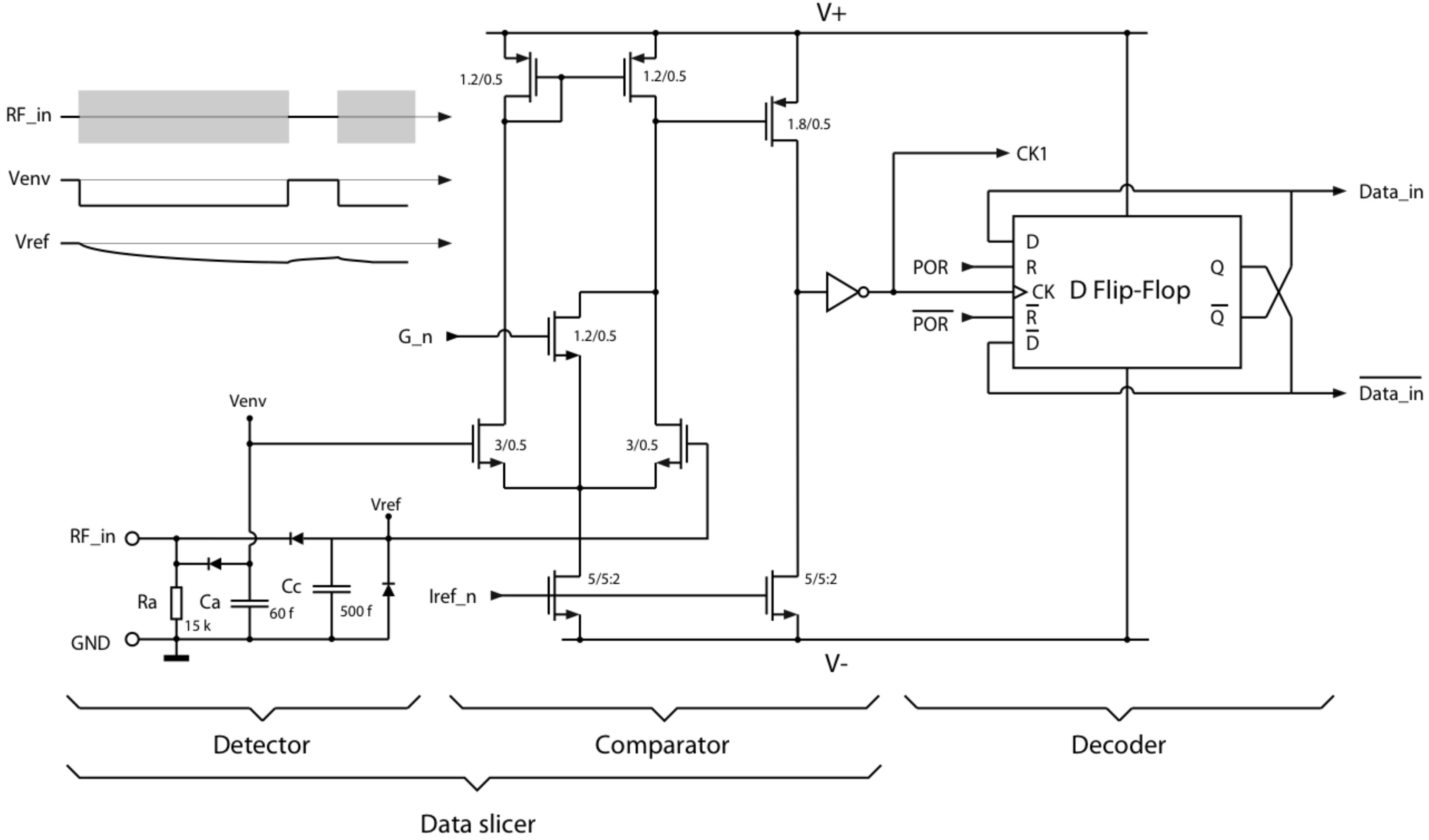
Building Blocks



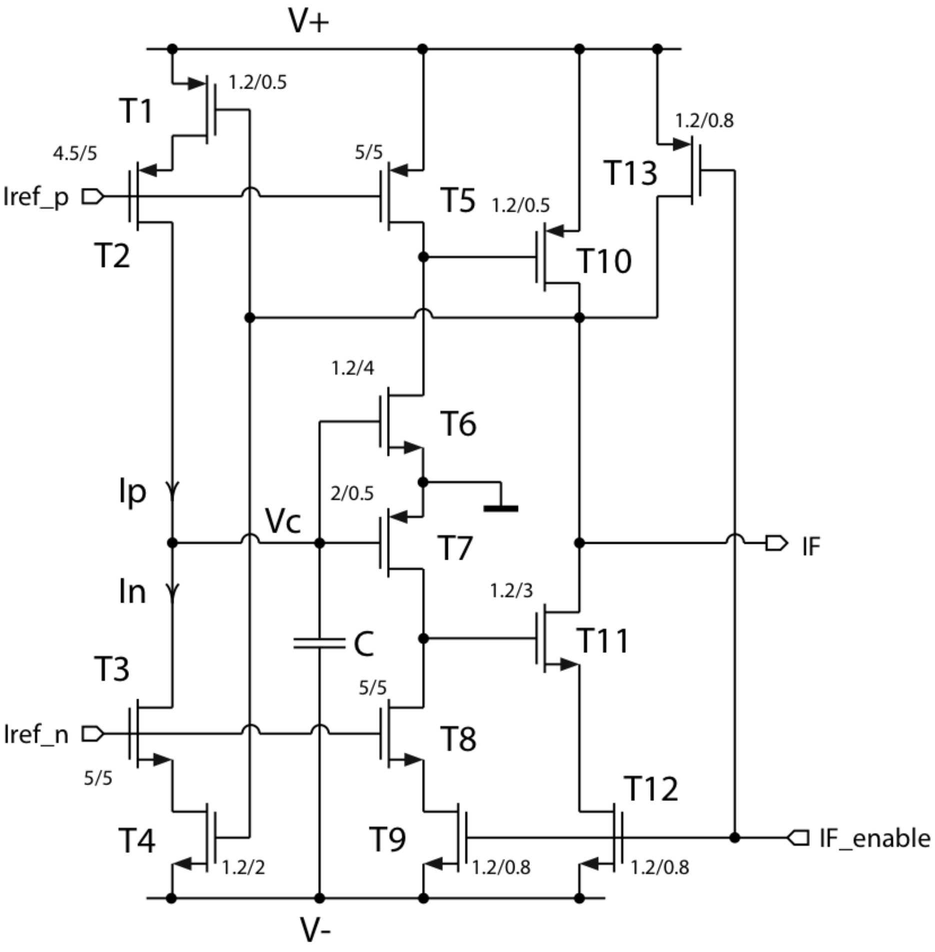
Rectifier
And
Voltage regulation



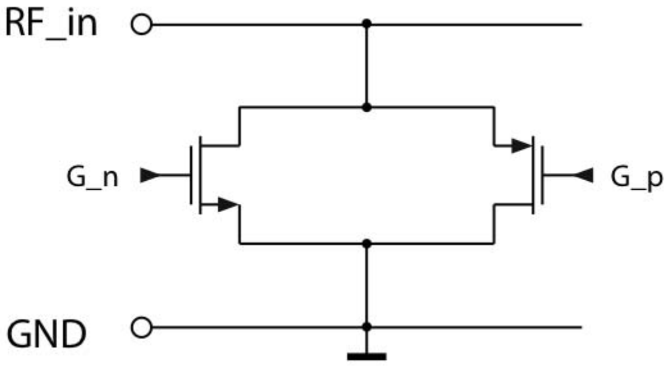
Detector + signal conditioning



IF Oscillator

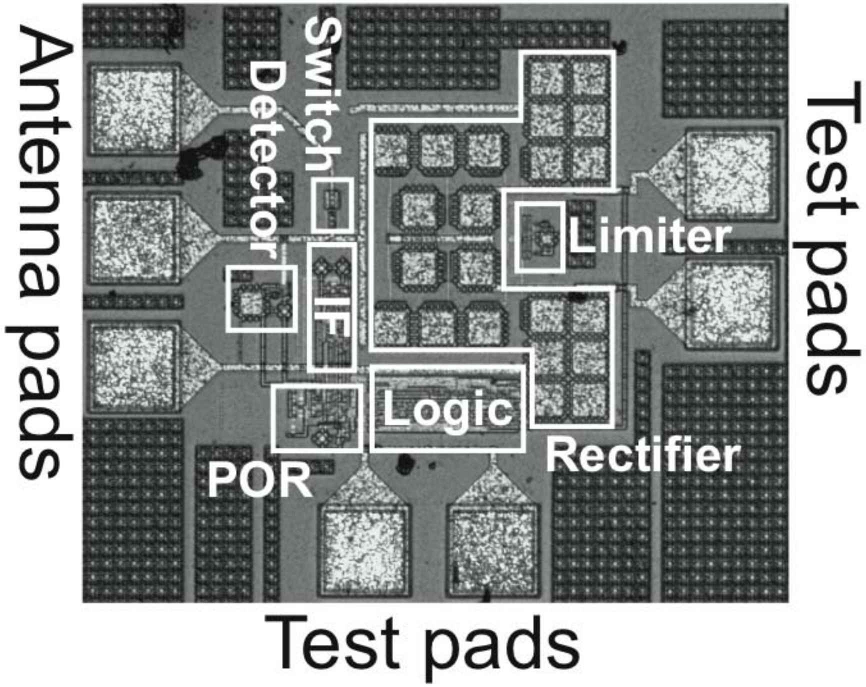


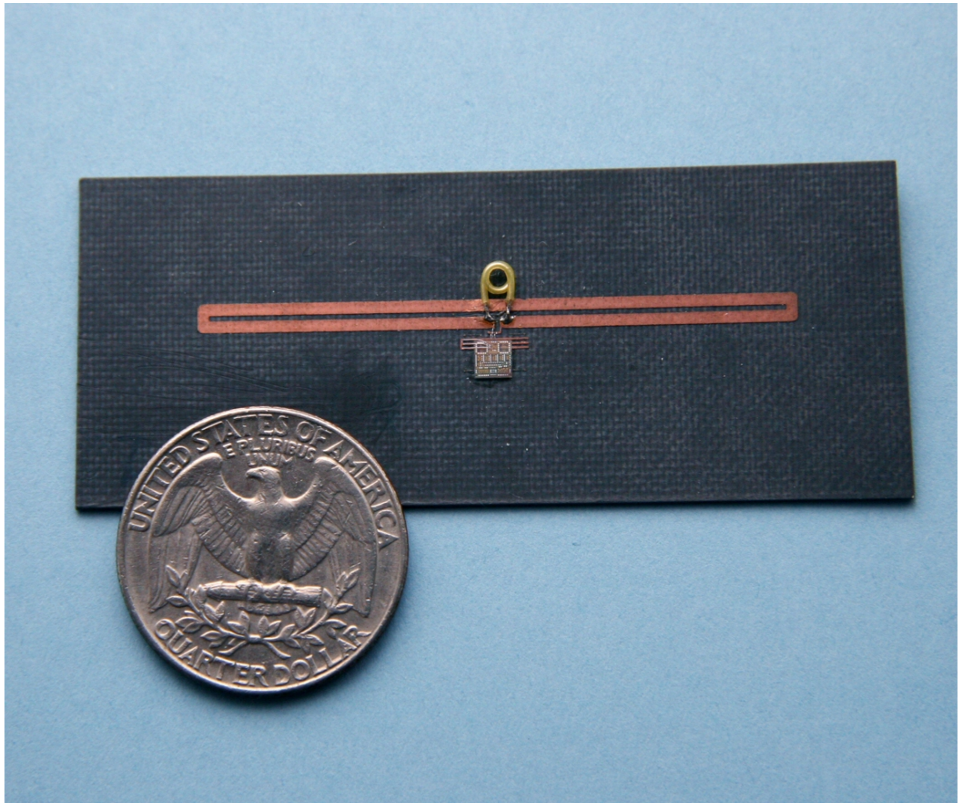
Modulator



Tag Die

Complete Tag with antenna





Reading Range

Frequency MHz	Antenna	Range m
2450	λ/2-dipole	6
2450	λ/2-dipole with inductive matching	9
2450	folded dipole	7
2450	folded dipole with inductive matching	12

At 12 m, the available power at the tag input is about 4.2 μW for a folded dipole (2dB gain)

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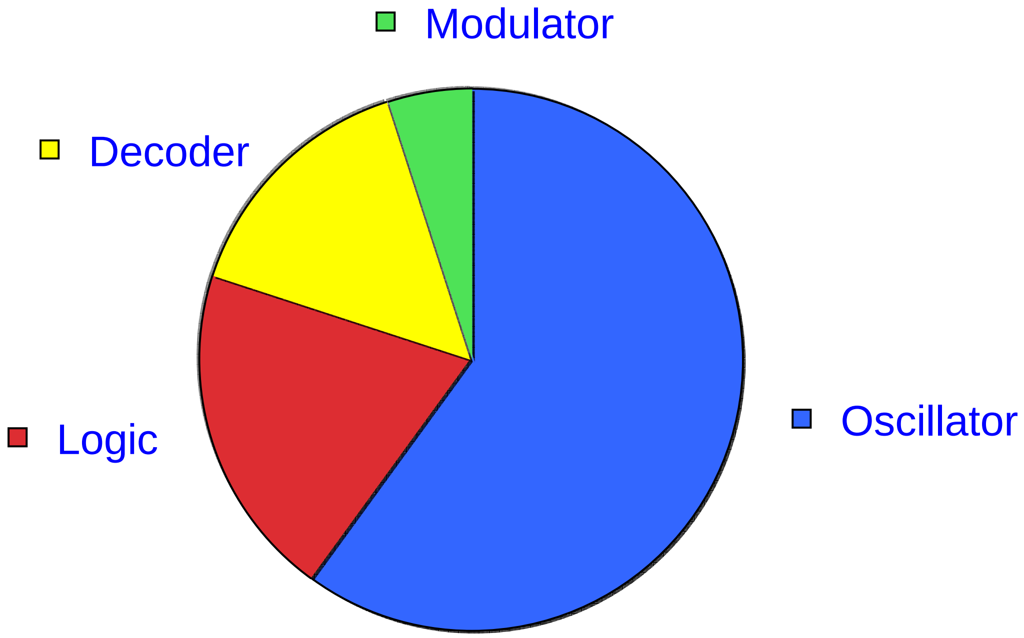
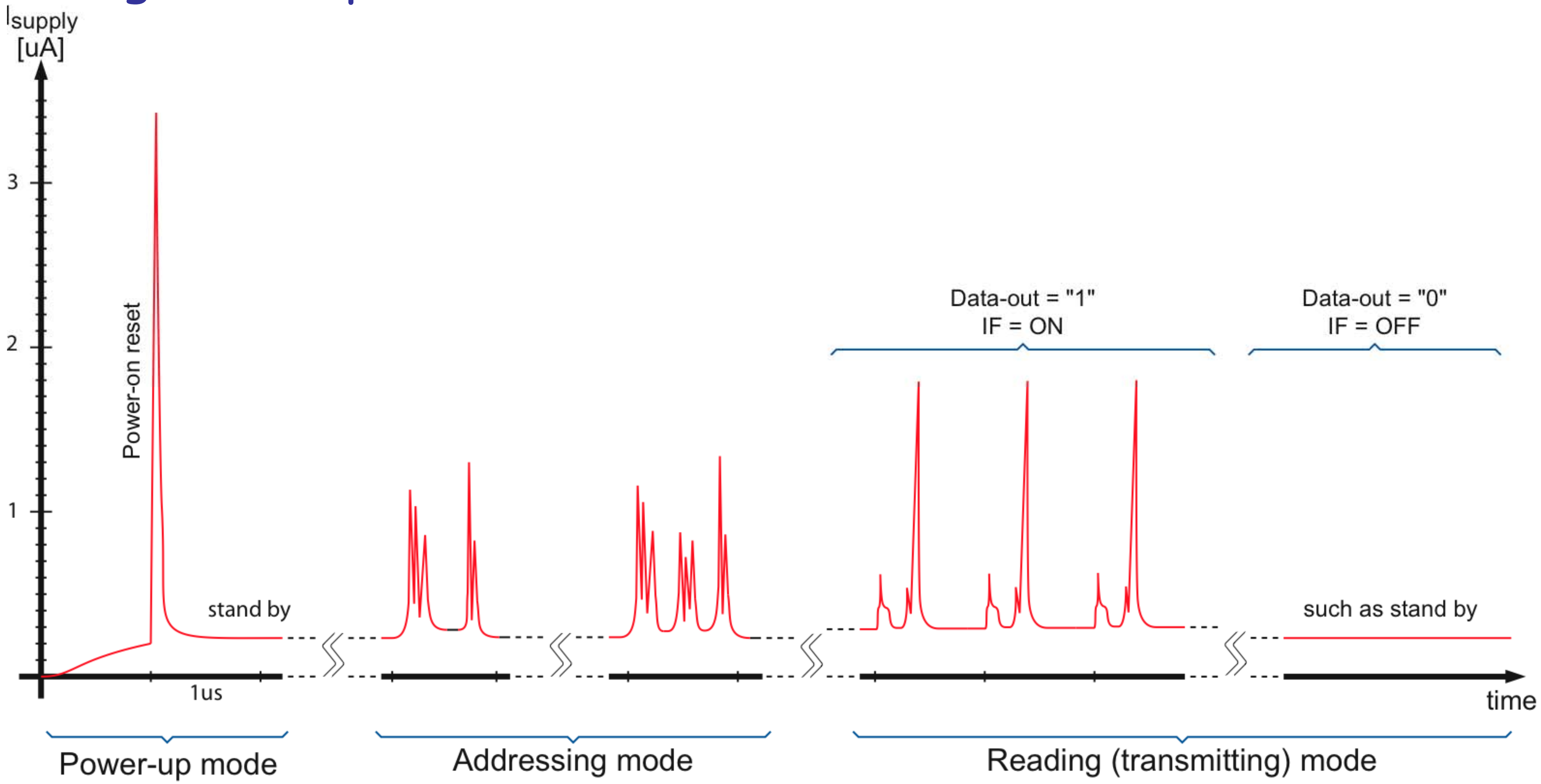
Power distribution between tag components



Power management
is the key issue !

Tag consumption



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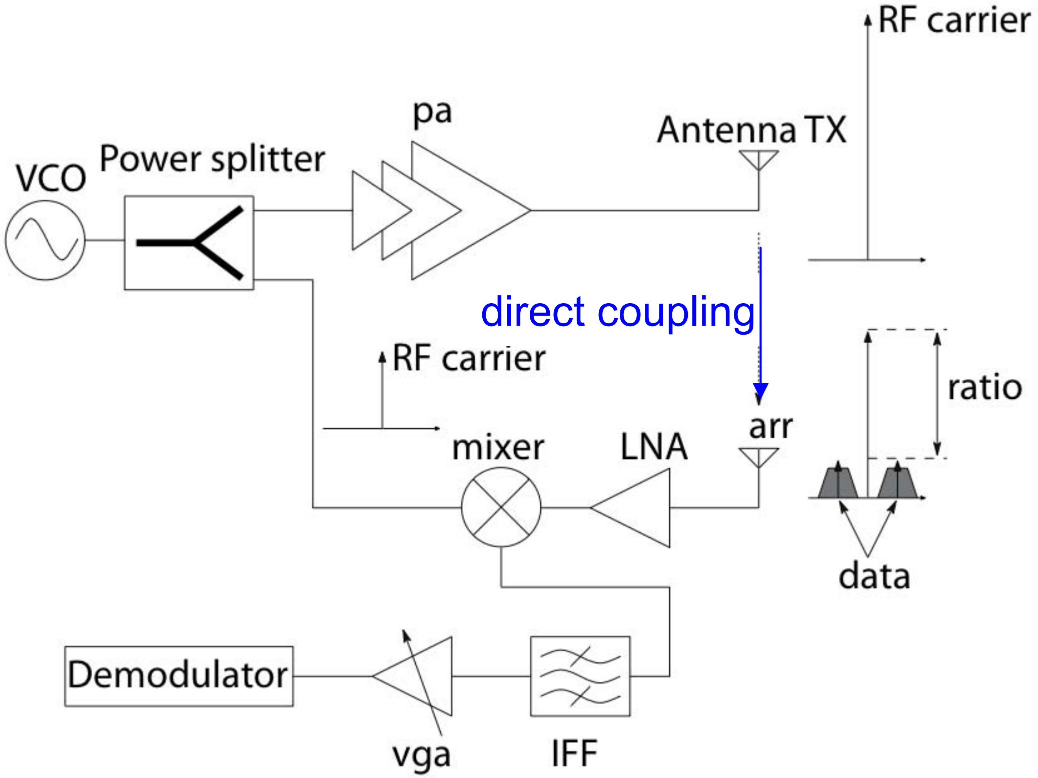
Basic RF Architecture



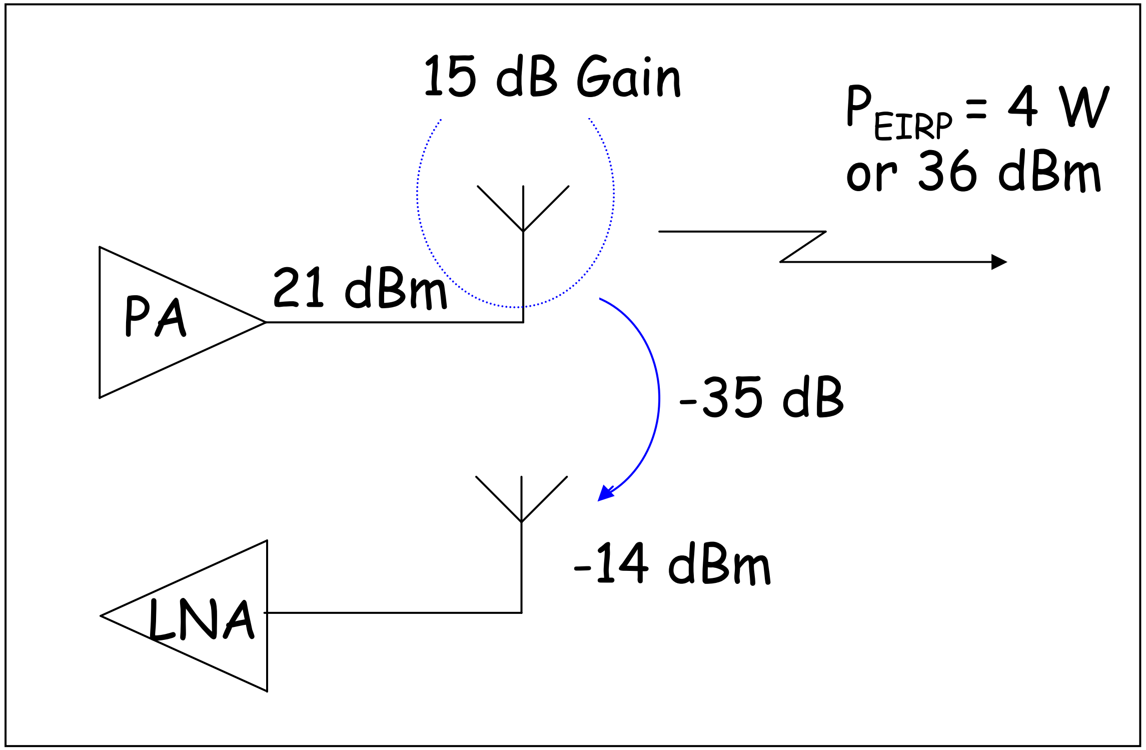
RF Front-end desensitization can occur due to direct-coupling effect
➔ *IP3* issue

Linearity or third order Interception Point *IP3*

It can be shown that

$$\boxed{IIP3 \geq P_I + 4.8} \quad \text{(dBm)}$$

where :
P_I is the interferer power and
IIP3 the System Input IP3



→ Spec. for overall system IIP3: > -14 dBm + 4.8 dBm = -9.2 dBm

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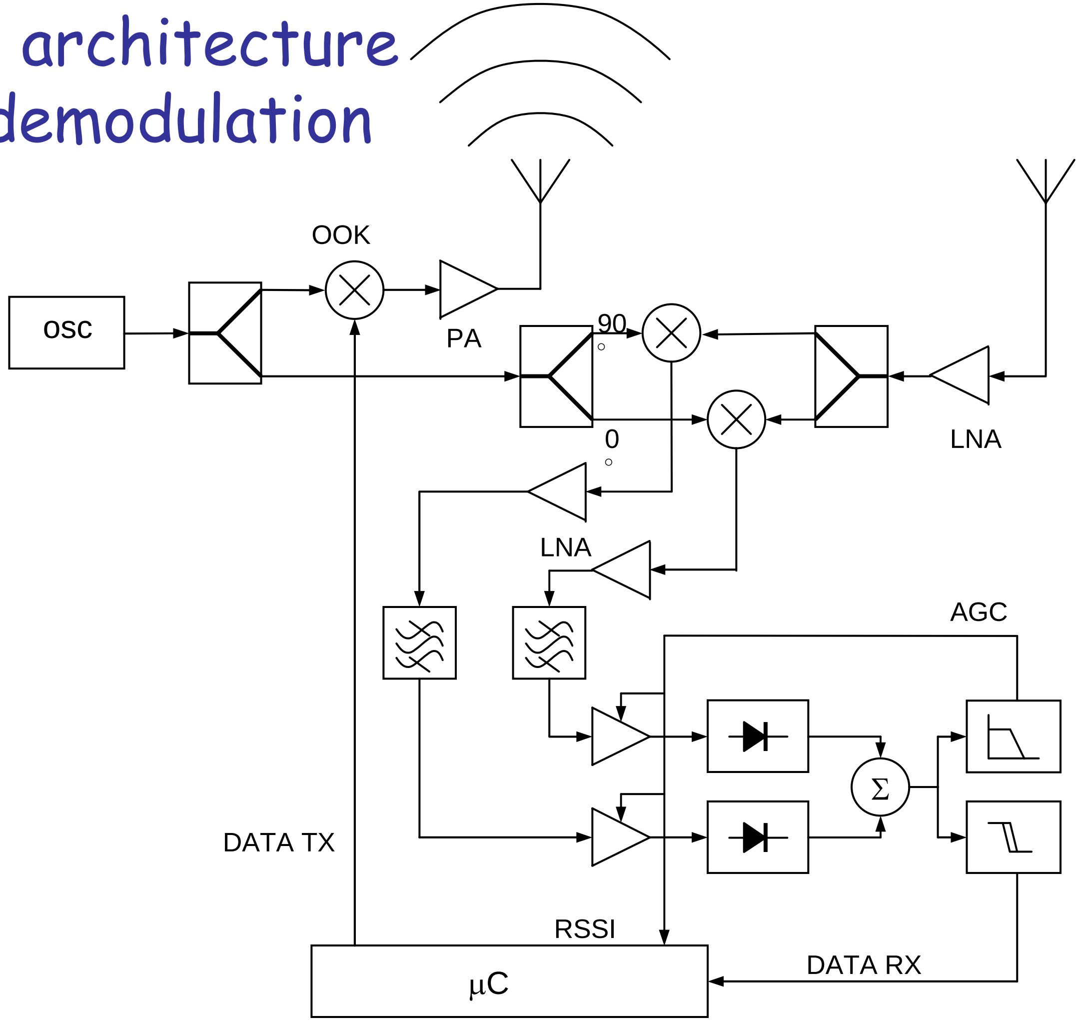
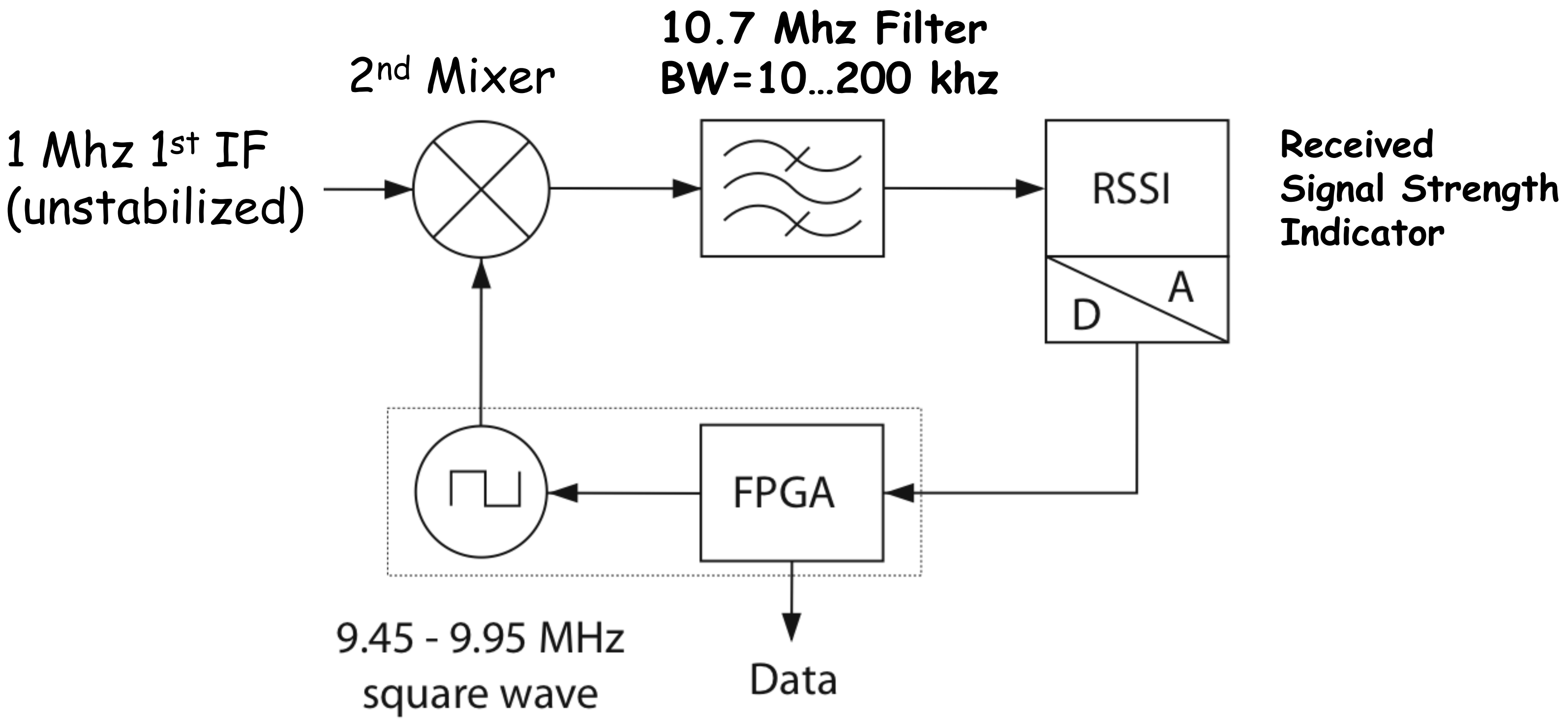
Advanced Reader architecture with quadrature demodulation



Advanced Reader architecture

2nd IF : Up-conversion with Frequency Sweeping Loop



michel.declercq@epfl.ch

5. CONCLUSION

michel.declercq@epfl.ch

Conclusions

- Wireless power transmission & rectifier models have been developed for optimizing the power supply available for the tag
- Different backscattering modulation types were compared and pPSK was identified as an excellent candidate given the naturally high input impedance of the tag;
- Readers's main issues were studied and optimized to achieve a sensitivity of -105 dBm @ BER = 10^{-5} & BW = 200 khz
- Power management of tag circuits and signal encoding has been carefully studied and proved to be a major issue in the overall performance
- A 2.45 Ghz tag IC connected to a folded dipole antenna and inductively matched led to a measured reading distance of 12 m;

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Dr. Catherine Dehollain
Dr. Norbert Joehl

For a detailed information on this topic, please refer to the book « Design and Optimization of Passive UHF RFID Systems » by the same authors, published by Springer (Sept. 2006)

michel.declercq@epfl.ch