International Summer School **Wireless Power Transmission for Space Applications**

Lightweight and low-power system for localization and powering of distributed devices

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WIPE

COST IC1301

Agenda

» Ambient “smartification”

» Terrestrial and spacial scenarios

» Circuit-level design of a smart reader:

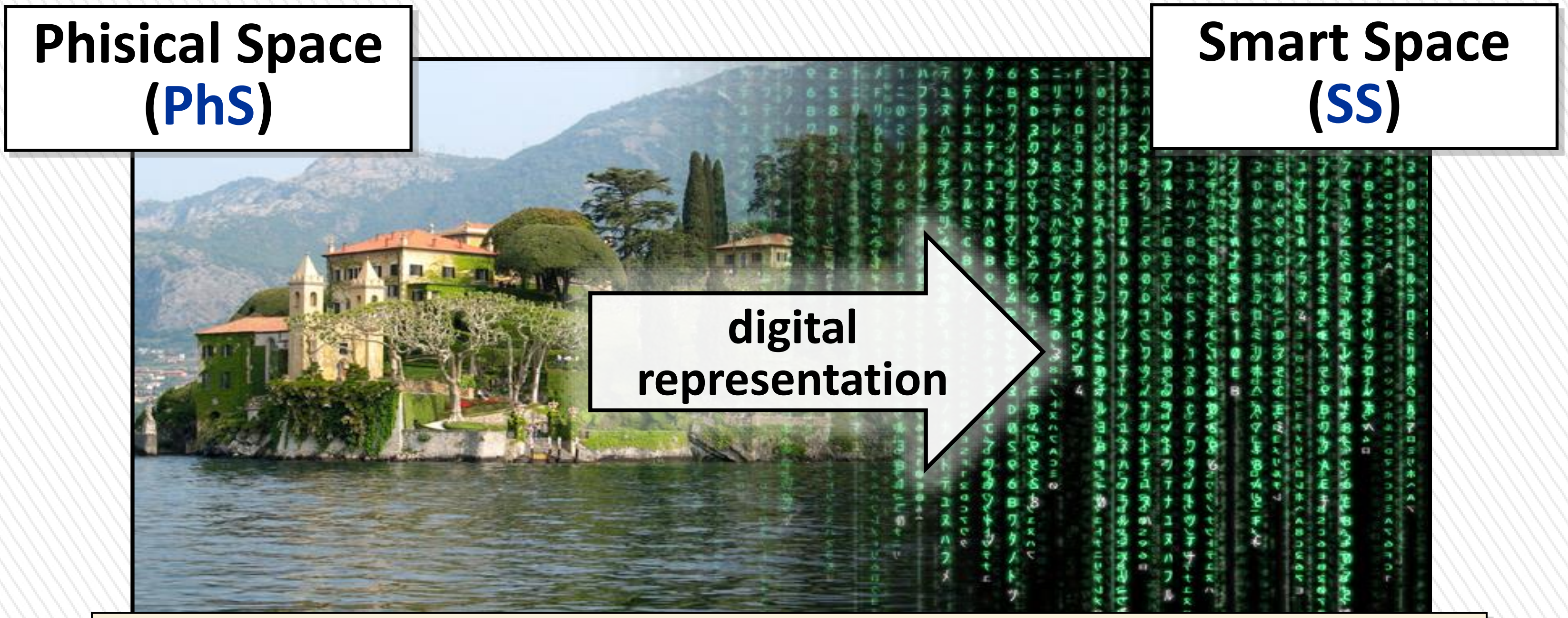
Objects ***detection, selection*** and ***powering*** “on demand”

» Terrestrial operation demonstration

» Conclusion

“Smartification”

» ***Smartification*** is the word we use to name the process of creating the digital representation of physical world in the ***Smart Space*** (SS)



- Easy to access information of the environment
- *Ambient intelligence:* almost unlimited applications

“Smartification”

» WSN and RF-ID are currently the enabling technologies for real-time and low-power ambient monitoring

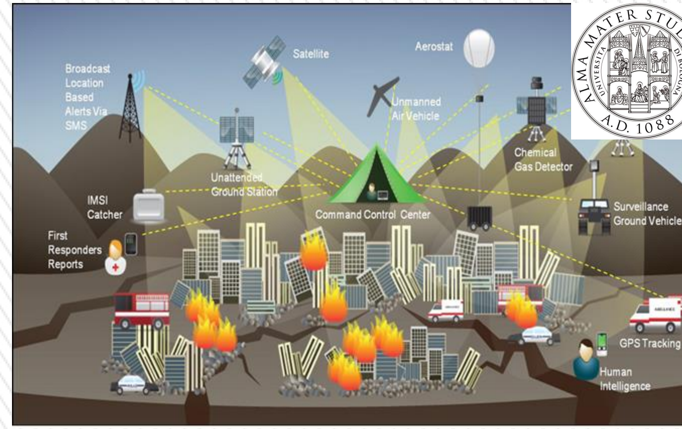
» Different challenges:

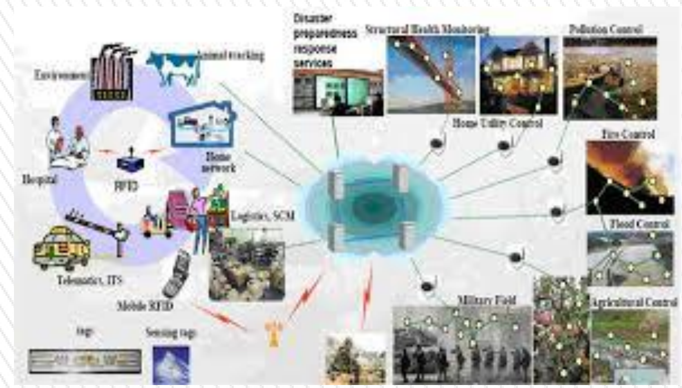
> Surveillance of remote area

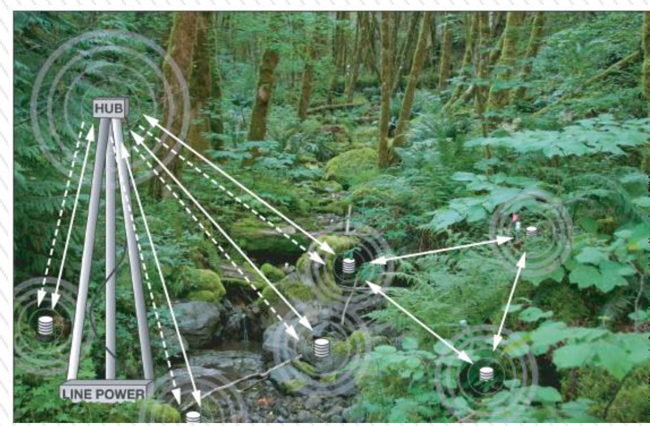
> Emergency communication

> Critical infrastructure

> Environmental monitoring





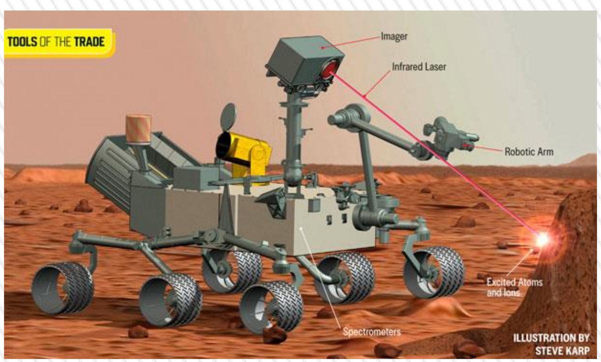


“Space sensing”

- challenges faced in space sensing and communication overlap with terrestrial examples of extreme environments:
  - hot or cold locations
  - high- or low-pressure enclosures,
  - critical control loops in aircraft
- Significant challenges for radio-frequency wireless sensing and communication
- Require state-of-the-art technologies to generate robust and affordable solutions esperienced in harsh environments

WPT for space sensing

- Remote power supply of probes and instruments deployed on the surface of the Moon and Mars (short range)
- Transmission of medium/low power levels (< kW) (*generated on the surface of the Moon/Mars*) from a base vehicle to supply fixed users or moving rovers/probes within a limited distance range.
- Power transmission between a source and a specific target with the target to be interrogated



Smartification of physical space

» Enabling technologies for the automatic development of a Smart-Space (SS)

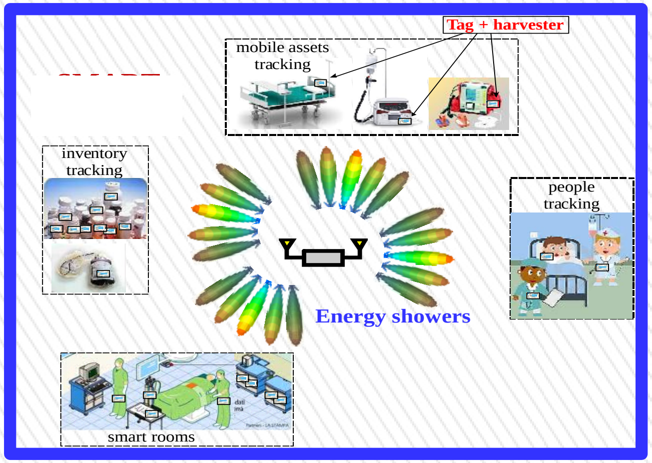
> *RID*: RFID-enabled reader @ 2.45 GHz

> Smart Object (RF-ID reader) wirelessly connected to a central unit (SS), able to remotely select or detect targets by means of EM interference

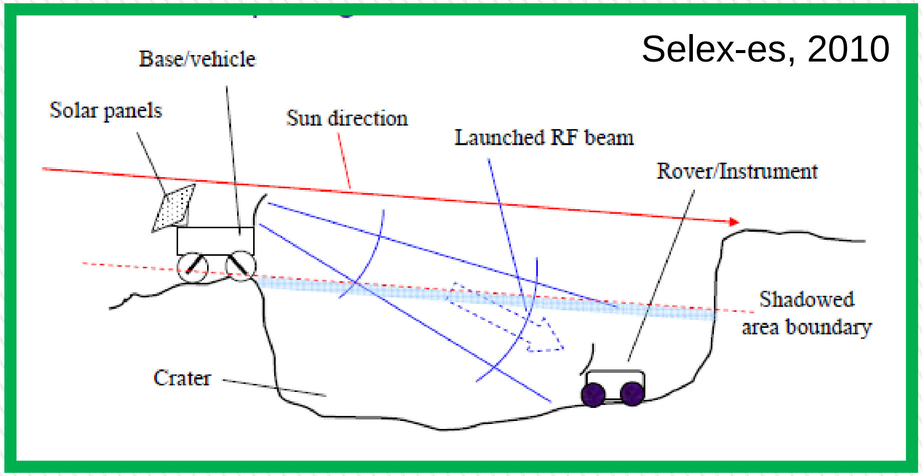
> Targets should be battery-free and equipped with some intelligence to be exchanged and updated several times for several purposes

smart RF-ID reader

industrial/civil ambient exploration

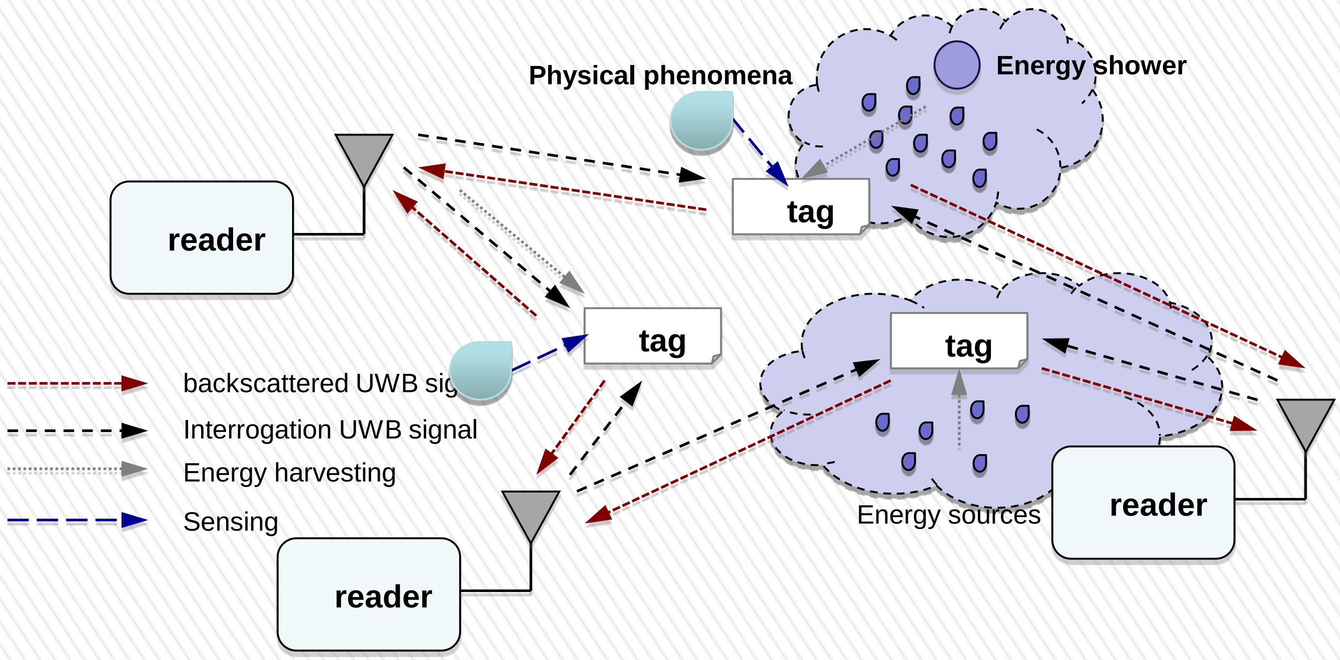


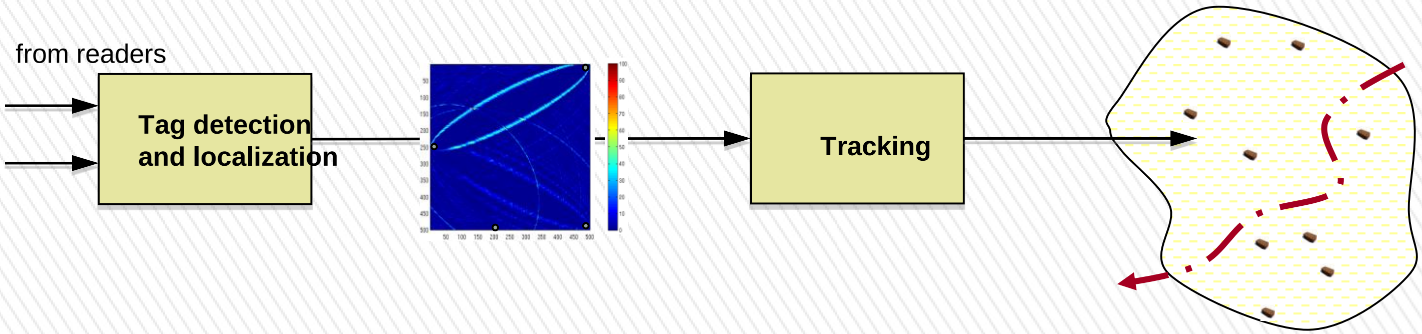
planetary exploration



Possible implementation Scenario

GRETA ITALIAN project GRETA (“*GREen TAgs and sensors with ultra-wideband identification and localization capabilities*”).





Possible tag layout

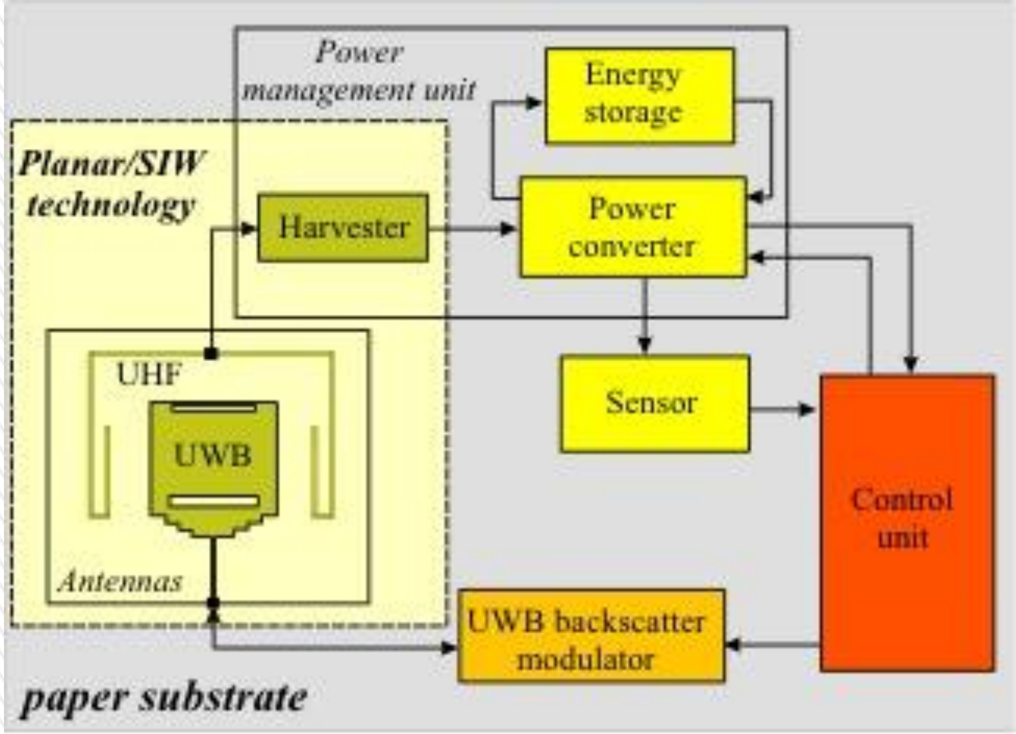


Figure 2: Tag architecture

Smart RF-ID reader

- Innovative RFID reader topology @ 2.45 GHz characteristics:
  - Select/discover closely-spaced and moving tagged objects, interact with them exchanging information
  - Combines the ***mono-pulse RADAR*** principle and ***electronic beam scanning***
  - Faster and lower-cost with respect to indoor localization techniques
  - Overcome severe fading by signal-processing-free solution
- System validation in indoor realistic scenarios
  - The reader selectively interacts with tags in static condition
  - The reader retrieves a sequence of moving objects

Motivations

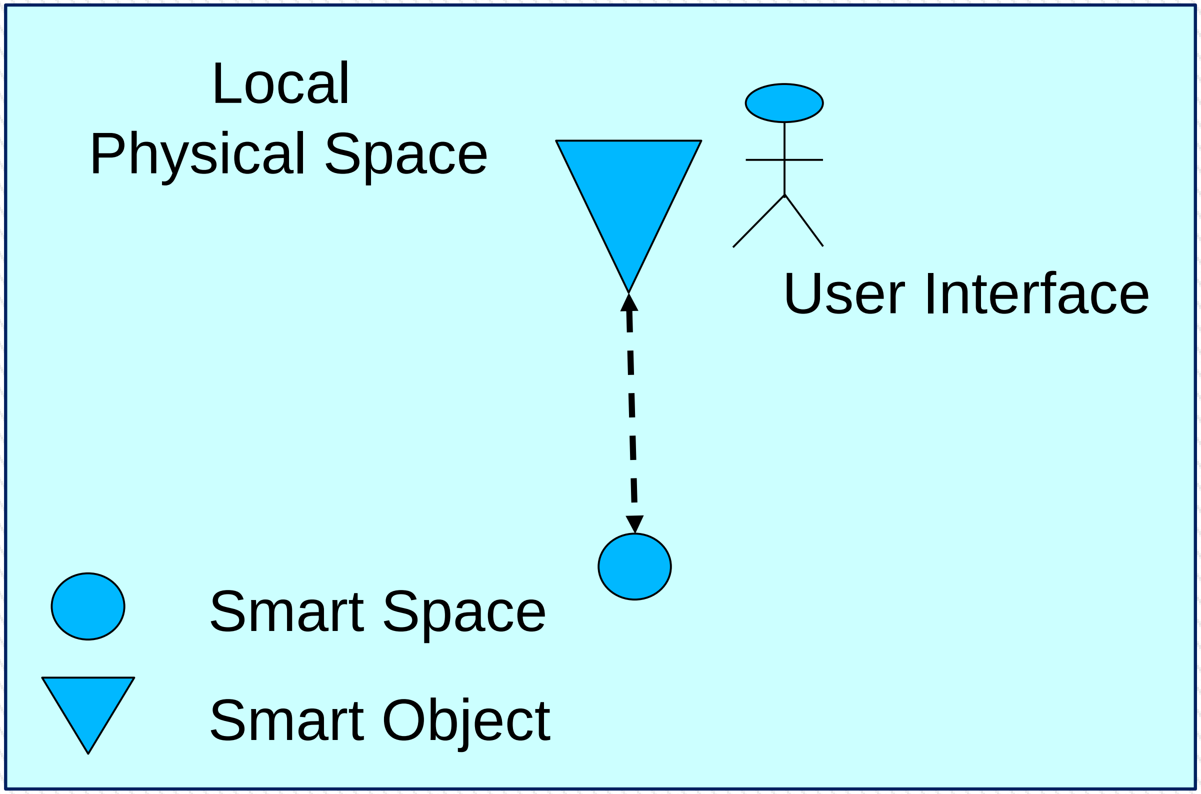
» Increasing interest in intelligent ambients
  > Availability and possibility to deploy systems of devices (sensors, actuators) energy autonomous
  > Improvement of living conditions and/or facility management

» Drawback: the numerous electronic devices distributed in the environment do not fully inter-operate

» The Bologna research unit activity aims to provide an innovative contribution towards the idea of the ***internet of things***

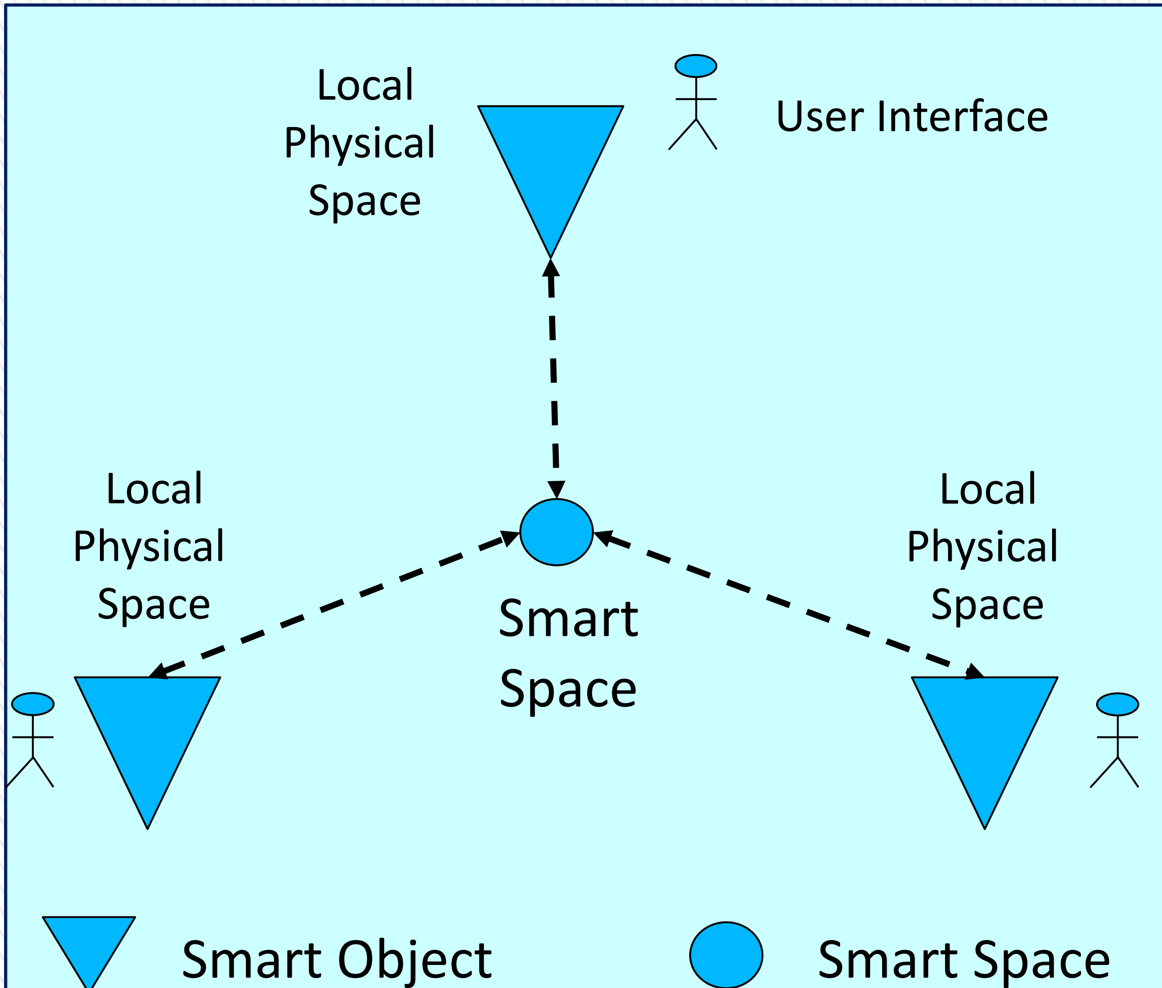
Smart Interaction Object

» Essence of a ***Smart Interaction Object***:
Enabler of Smart Space mediated Interaction



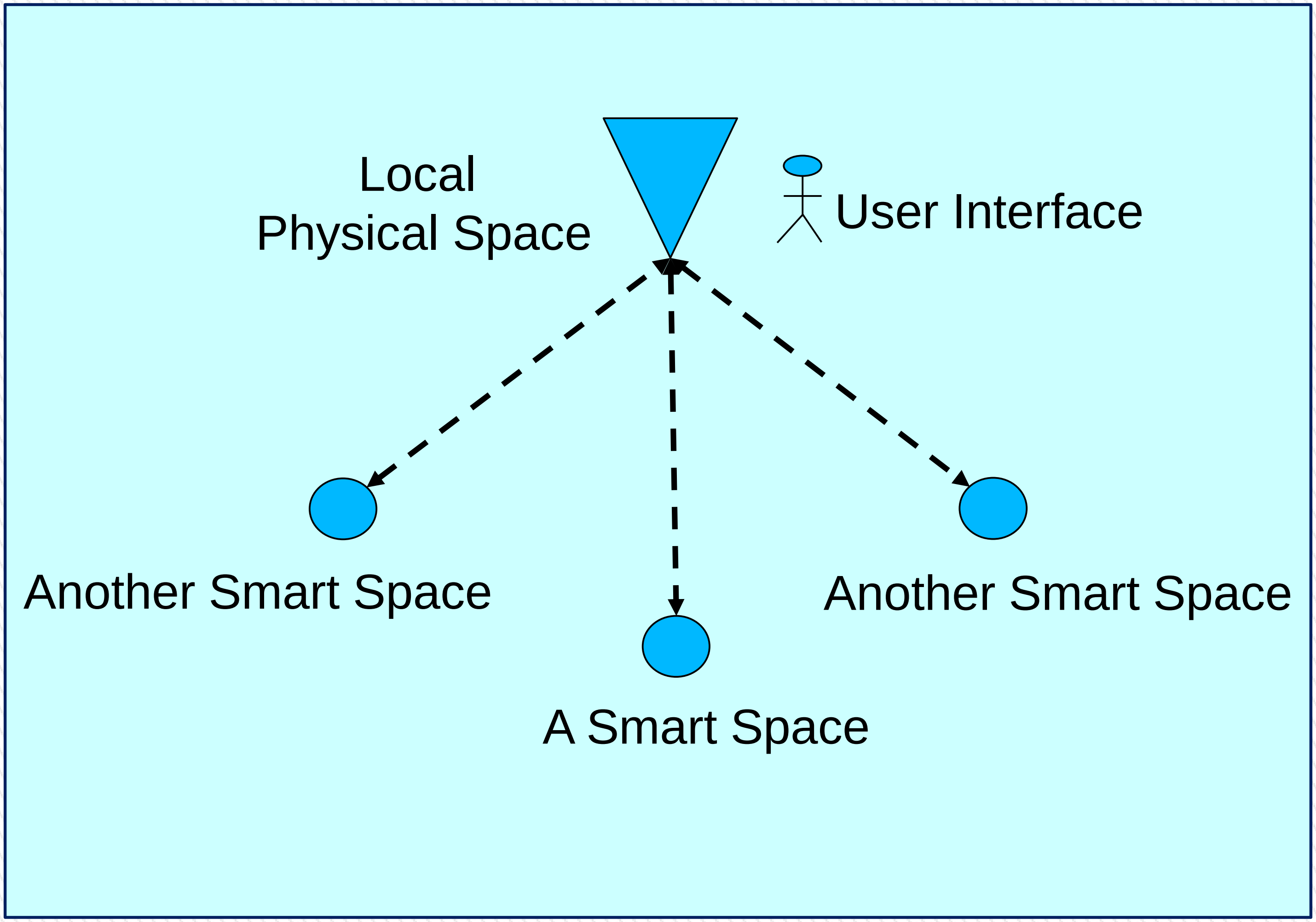
All
prototype devices
comply with this
architecture

Enabler of co-operative, environment-related applications



1. Interaction with the environment based on global knowledge
2. Connections between objects
3. Connections between people
4. Environment to user communication
5. Environment digitalization

Dual approach (i.e. Smart Object centric) is also valid



Smart ambient application in civil and industral plants

- ***Goal***: interoperability of physical information and communication aspects

objects must communicate and share their status (by means of sensors/RFID applied on them)

- Our approach is demonstrated by considering the **management and maintenance of complex spaces**:
  - Detection, localization and identification of (possibly) hidden items
  - Items information storage and update
  - Automatic request of item maintenance

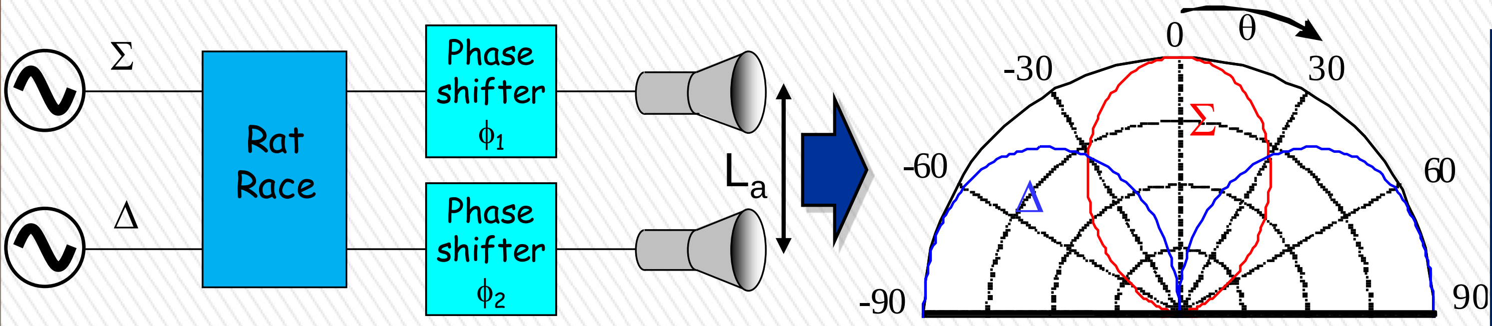
Smart RF-ID Reader solutions

- ***Remote and selective identification*** by readers is a key issue in SS
  - Traditional RFID readers usually collect objects codes (IDs) in their reading range *with neither selectivity nor interaction capabilities*
  - ***Operating failure*** may occur when dealing with tags in harsh indoor environments
- *Expensive or less accurate solutions* are available to overcome this problem:
  - Large and complex antenna array
  - Triangulation technique
  - Time-consuming signal processing (e.g. UWB method)

Not suitable for space applications

- *A reader with selectivity capabilities for IDs detection is needed*

Combining Monopulse-RADAR and Beam-Steering



Plane containing array alignment and broadside (θ=0°) directions

Δ array factor

$$F_{\Delta}(\psi)=e^{j\left(\frac{2\pi L_a}{\lambda}\cos\psi-\phi_1\right)}-e^{-j\left(\frac{2\pi L_a}{\lambda}\cos\psi+\phi_2\right)}$$

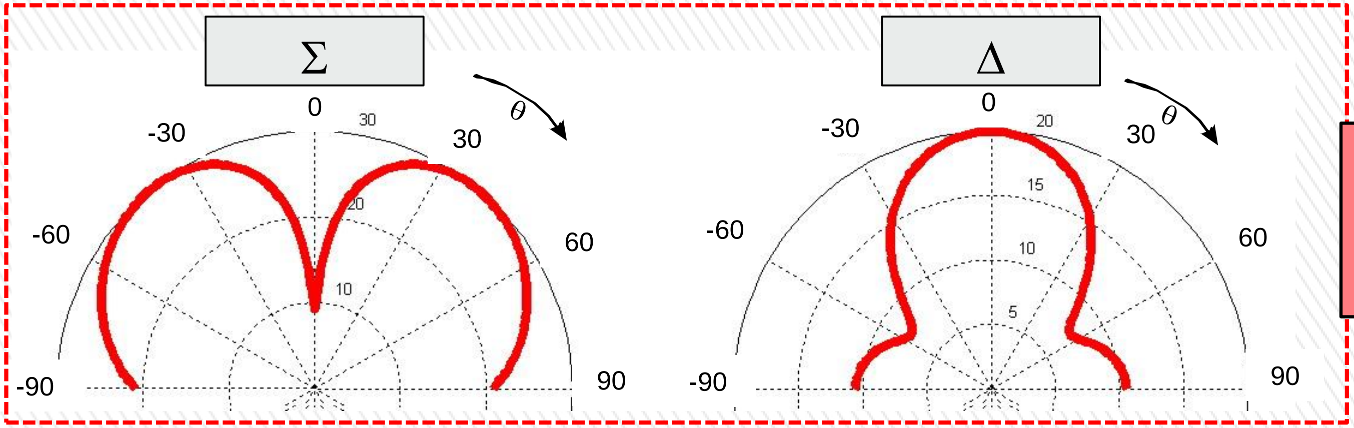
Σ array factor

$$F_{\Sigma}(\psi)=e^{j\left(\frac{2\pi L_a}{\lambda}\cos\psi-\phi_1\right)}+e^{-j\left(\frac{2\pi L_a}{\lambda}\cos\psi+\phi_2\right)}$$

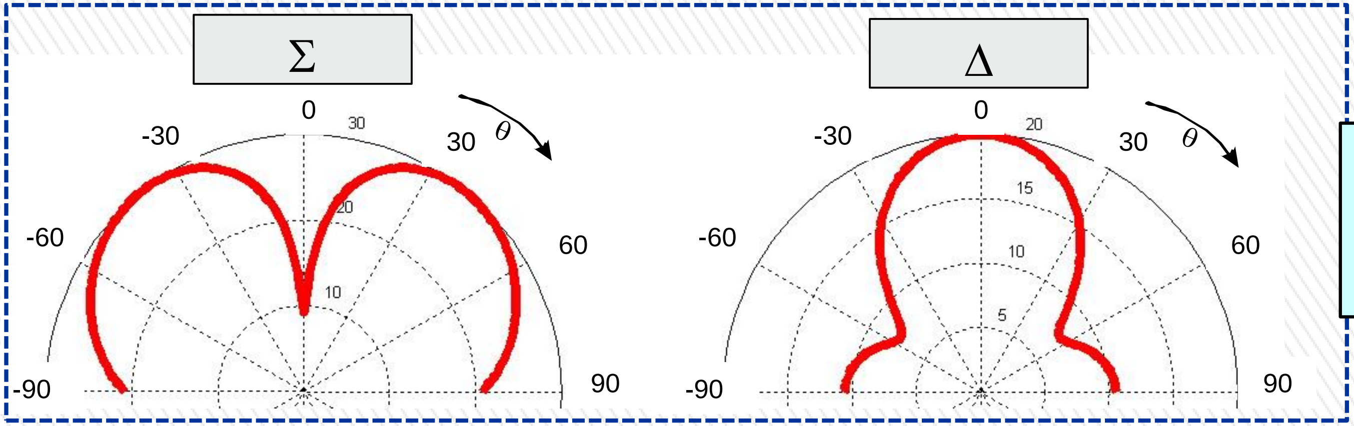
ψ angle formed by the array alignment direction and the field evaluation direction $\psi=f(\theta,\phi)$

- **Monopulse-RADAR**
  - Σ and Δ radiation patterns are obtained from the in-phase (Σ) and out-of-phase (Δ) ports of a rat-race coupler
- **Beam-Steering**
  - Σ and Δ patterns are steered by simultaneously controlling two phase-shifters (ϕ_1 and ϕ_2 phases)

Combining Monopulse-RADAR and Beam-Steering : simulated beahvior



Rotate left from the pointing position via ϕ_1



Rotate right from the pointing position via ϕ_2

- Sharp shapes allow the measure of the tag θ-direction with respect to to the pointed direction
- Monopulse-RADAR principle allows **2D localization** only

Beam-Steering and Monopulse-RADAR operation

- » *Monopulse-RADAR* allows to select objects in close proximity
  - > *Sharp shape* of the Δ-pattern around nulls is essential for the resolution
- » The minimum distinguishable tags distance improves with sharpness of the Δ-pattern (*array resolution*)
- • *Fading effect* reduces the resolution of the monopulse-RADAR
- » *Beam-Steering* around pointed directions allows to:
  - > Overcome the NLOS paths that could randomly dim the Σ- and Δ- signal
  - > Identify the relative locations of the others tags with respect to the pointed direction
- » *System Operation*
  - > For each θ-direction, the reader collects the RSSI at the Σ - and Δ- ports
  - > ***Selection*** and ***Localization*** of the IDs are derived from the Maximum Power Ratio (MPR)

Objects *selection*

RID — remotely points to the wanted object

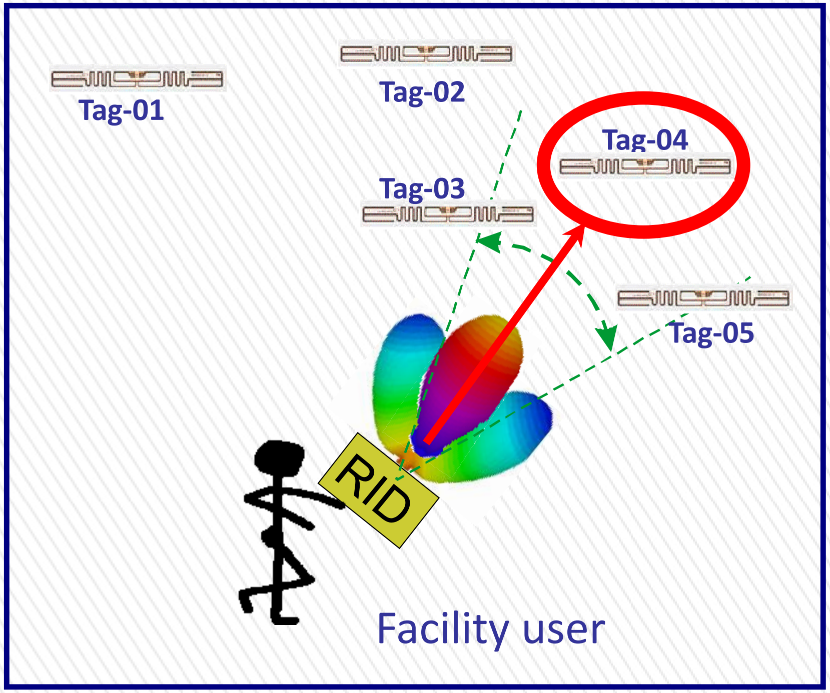
near-by tagged items are activated, too, due to:

- limited antenna gain
- fast fading

FAST SCAN around pointed position

IDs ACQUISITION by:
monopulse RADAR measure at the Σ and Δ RID ports of RSSI of tags placed around pointed position

DECISION: selected ID and its properties sent to the SS



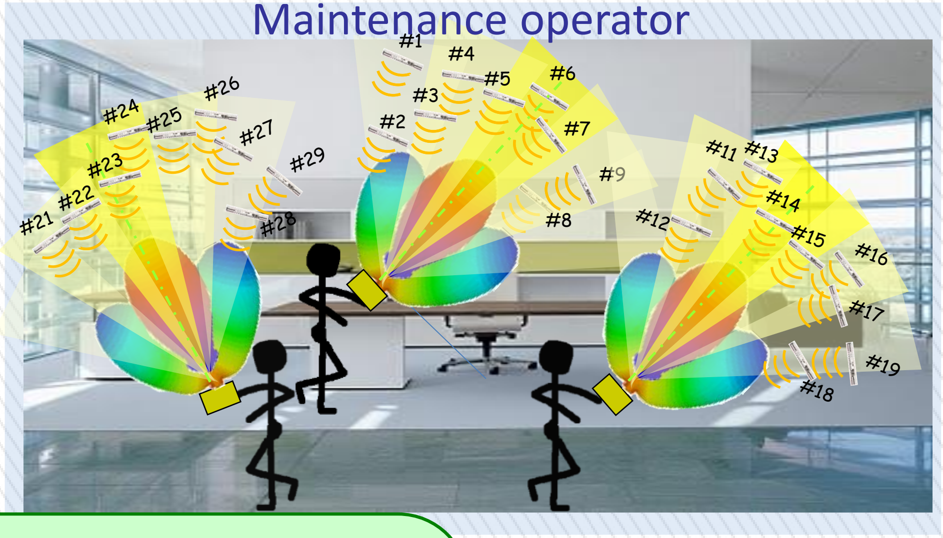
Objects *detection*

Smart Space

- drives RID to the required physical space
- the hidden tagged object is searched

RID

starts searching for the object with the ID acquired during "selection"



HIDDEN OBJECT DETECTION

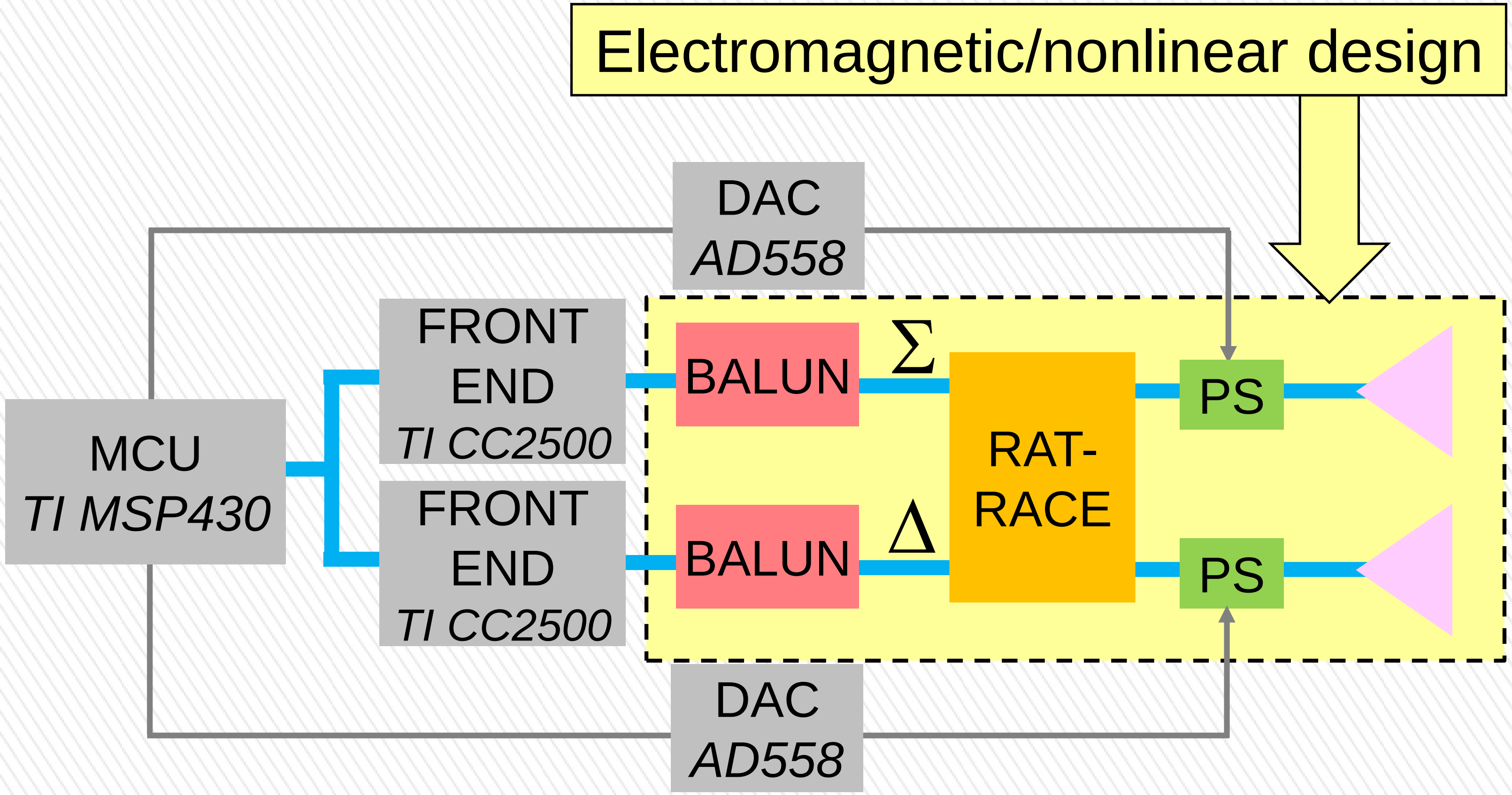
COARSE POSITIONING: activate closely spaced Tags ID ***detection*** by measure of RSSI at the Σ RID port (definition of the environment portion where ID is located)

FINE POSITIONING: monopulse RADAR measure of RSSI at the Σ and Δ RID ports of tags placed around pointed position (same as in selection mode)

performs action and update object properties/state

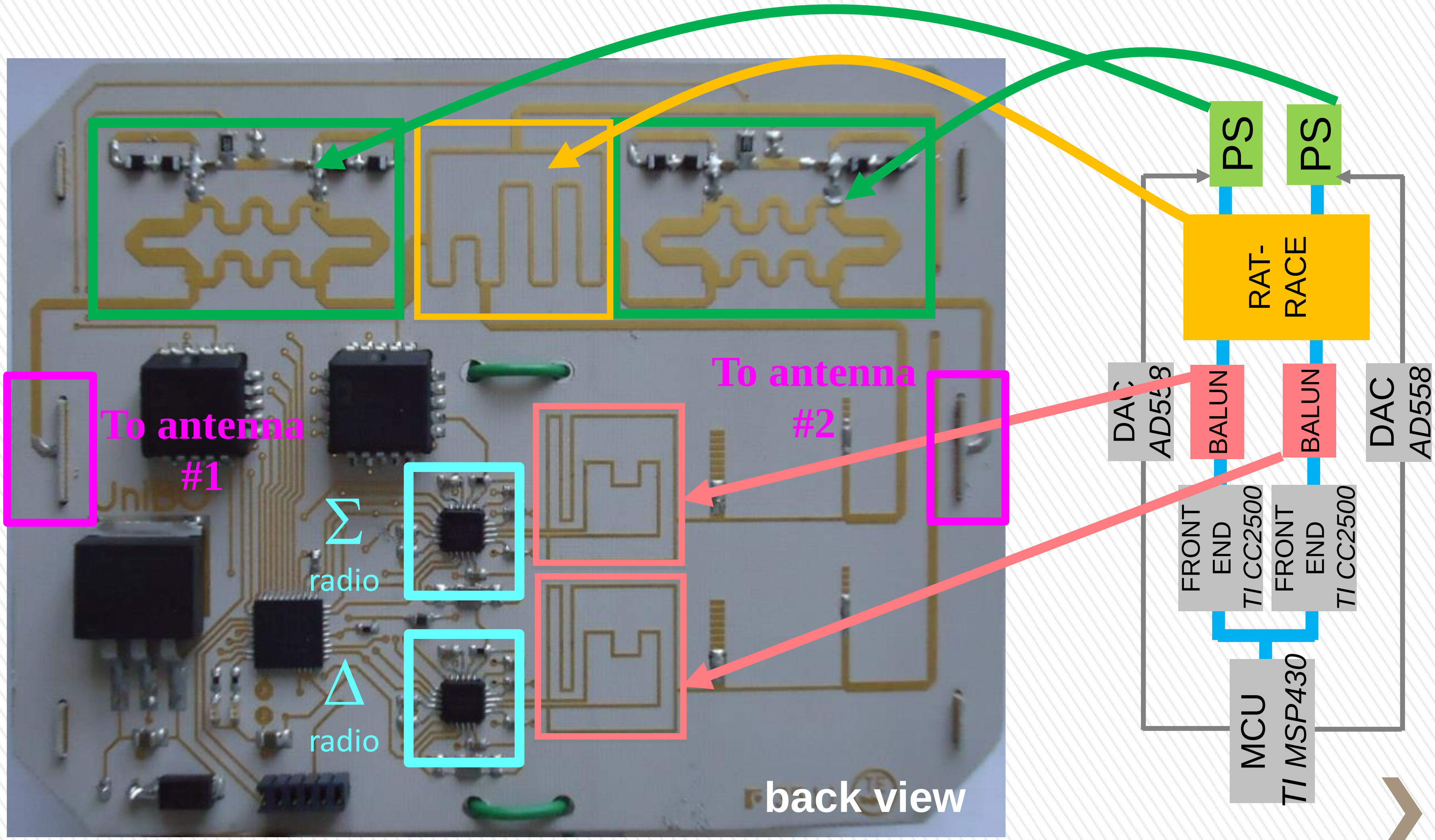
Smart Space

Block diagram of the RID



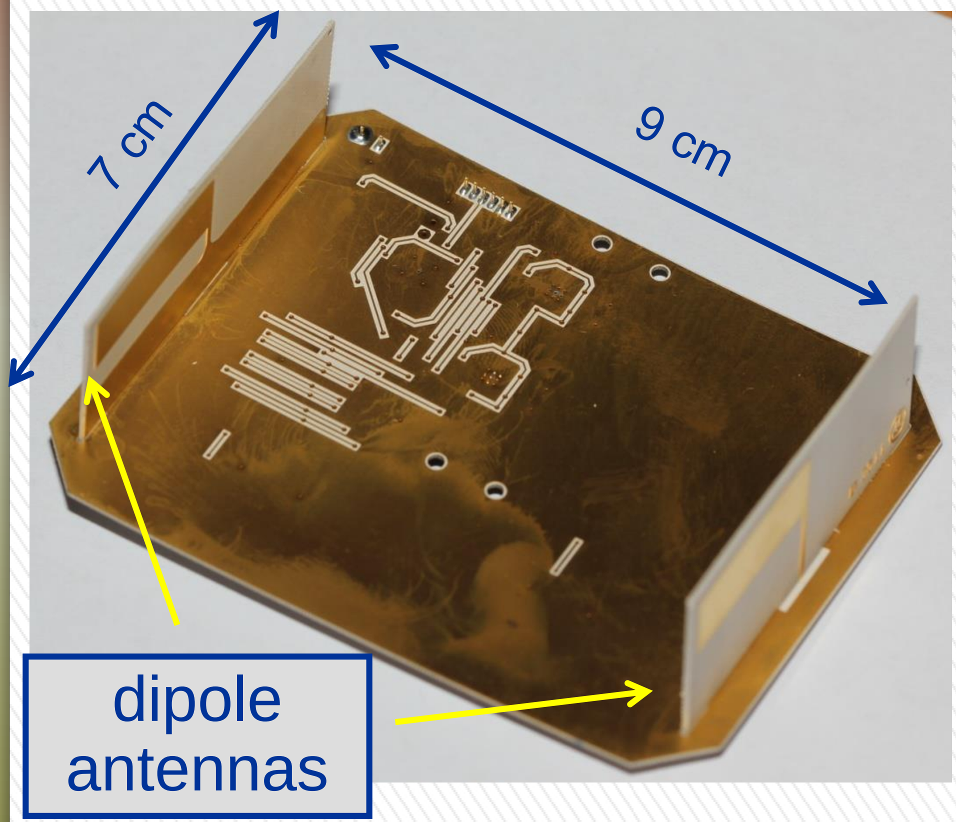
commercial ICs

The RID layout



Layout-wise co-design of the microwave circuits connecting commercial chips

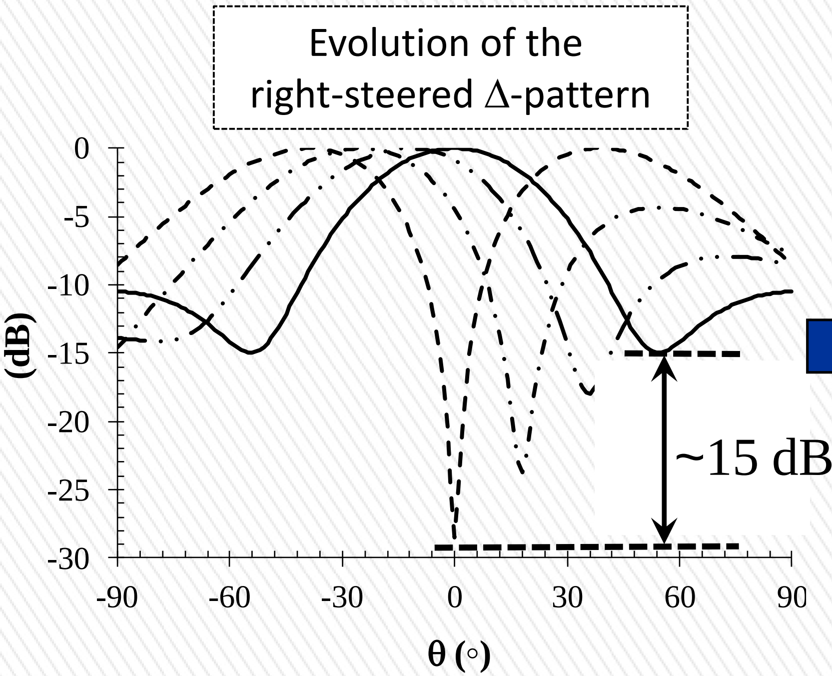
The RID prototype

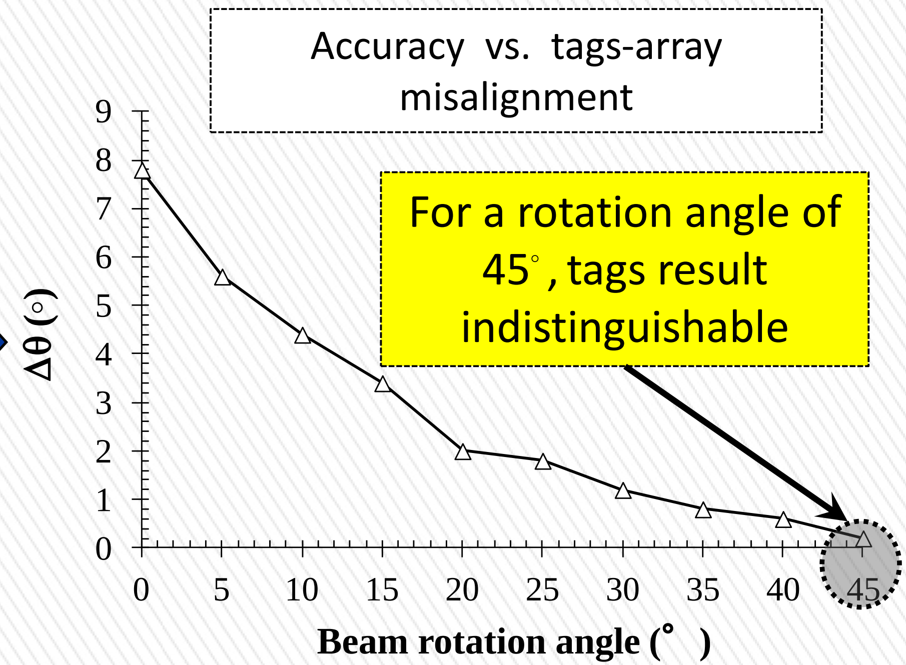


- *Two dipoles* are locked together and placed orthogonal to the ground-plane of the printed circuit.
- Array behavior influenced by the ground plane for both *near-field* and *far-field* performance prediction.
- Strategic issue: *antenna selection* in order to have good selectivity and almost constant behavior in the scanning zone.

Beam steering and Resolution

Array resolution drop off over the reading zone as the Δ- and Σ-patterns are steered with respect to the reader pointing direction





While steering, sharpness degradation is observed

- Tags placed far laterally with respect to reader may be grossly localized

NOTE: using *high-directivity array* reduces the *READING ZONE* of the system

Antenna Design for Monopulse-RADAR with Beam-Steering

- » The array directivity is an issue in *Monopulse-RADAR* with *Beam-Steering* solution and is selected based on conflicting needs:
- » In fact, increasing *antenna directivity :*
  - > *Enhances* the Δ-pattern *sharpness* *(*array resolution) around its nulls
  - > *Enhances robustness with respect to fading effects*
  - > C*auses* significant variations of Σ- and Δ- patterns while *beam-steering*

trade-off between:
array resolution *and* wide angular reading zone

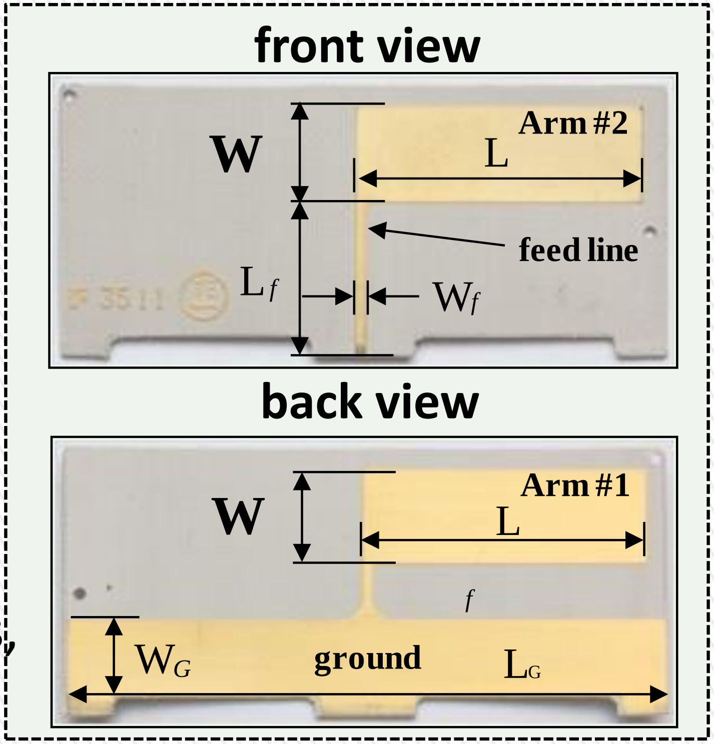
- Antenna array design goals:
  - low array directivity
  - maximum radiation efficiency
  - minimum back-radiation
  - minimum overall antenna dimensions

Our choice: low-directivity array

Design of Flag-Shaped Printed Dipole Antenna

Two printed flag-shaped dipoles to meet:

- Low-directivity and high-efficiency antenna array
- Light-weight, compact size, ease of manufacturing
- no need for space-consuming balun



» Optimization process

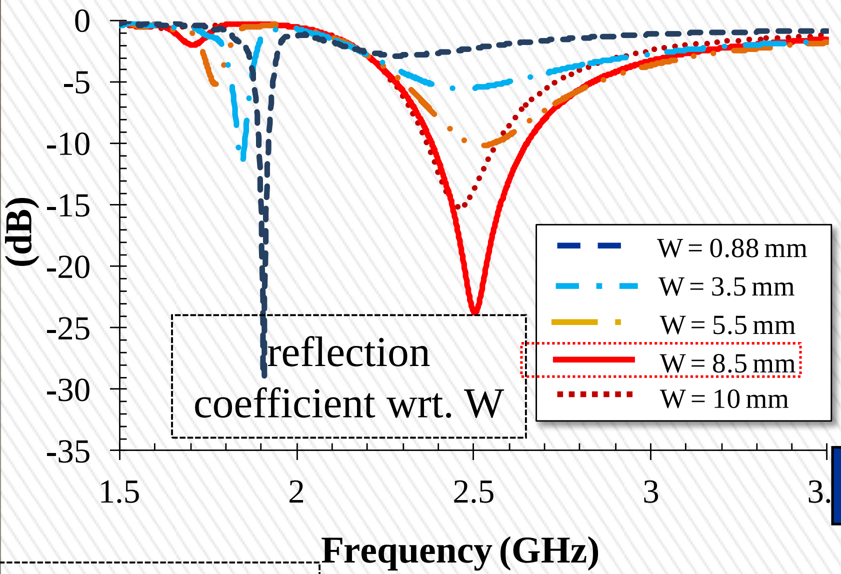
> To reduce the overall antenna dimensions, the dipole width (W) is increased

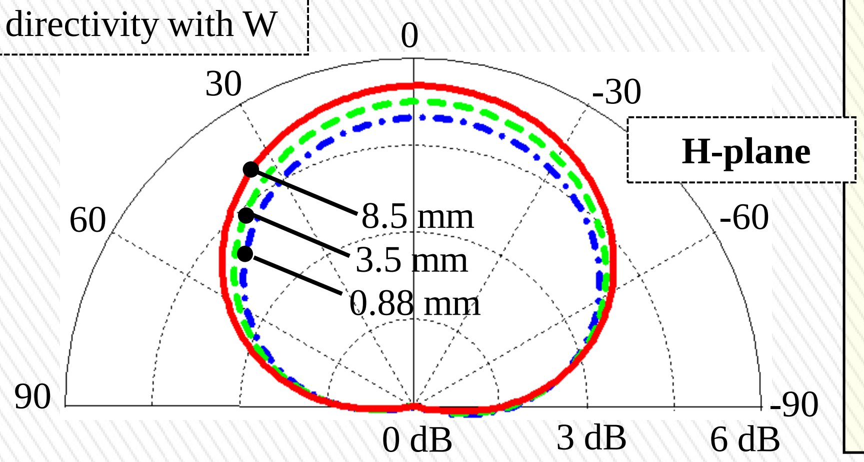
+ It provides a shorter electrical length by exploiting the *edge capacitive effects* ($L<\lambda/4$)

> To reduce *back-radiation* the reflector dimensions (W_G and L_G) are optimized

> The optimum lengths of L and W provide minimization of the *return loss*

Printed Dipole Miniaturization

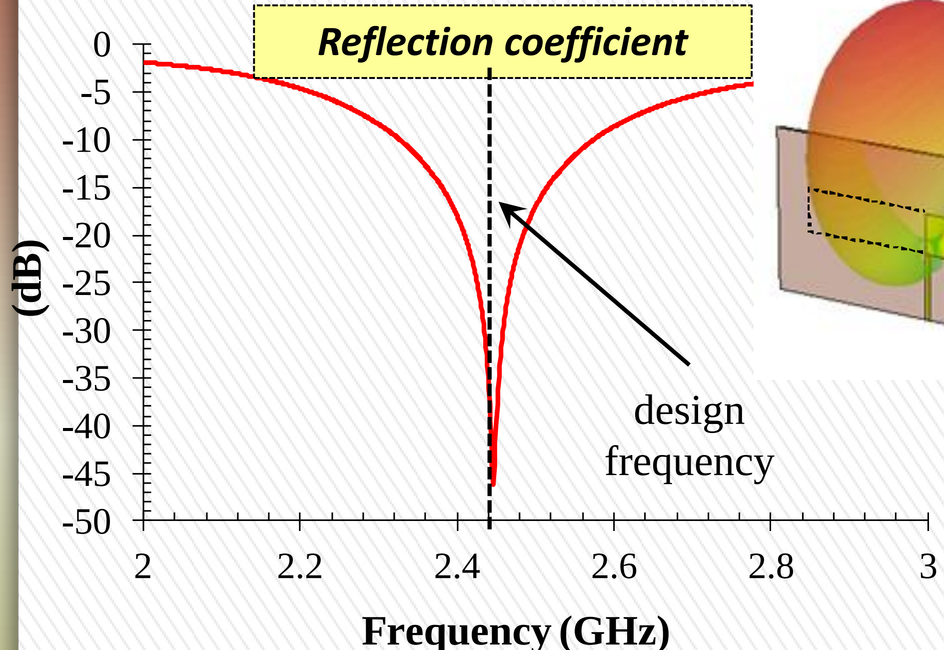


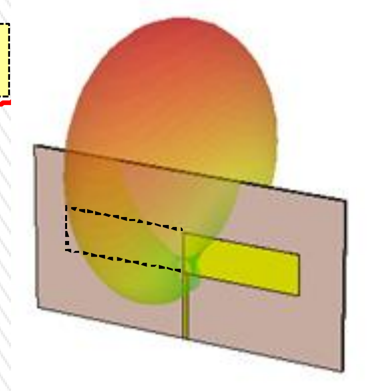


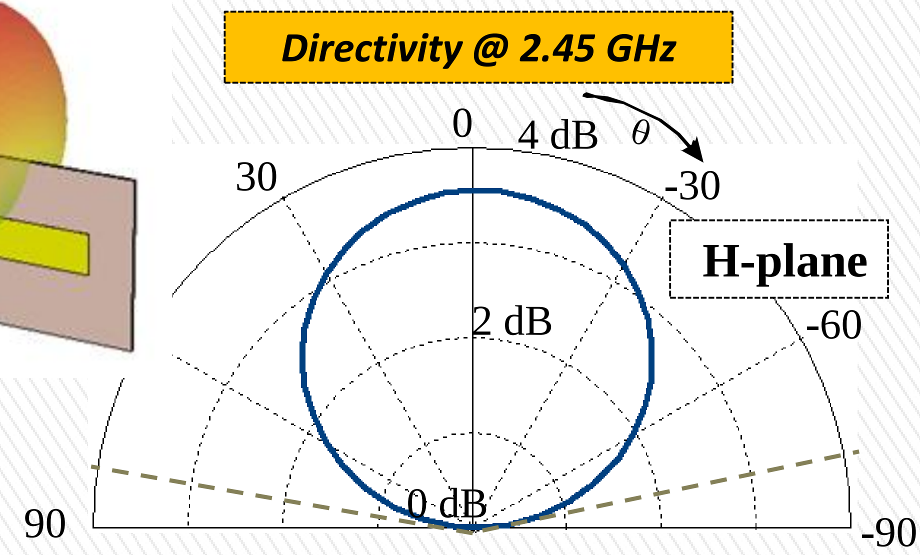
Antenna benefits from the optimum dipole width W :

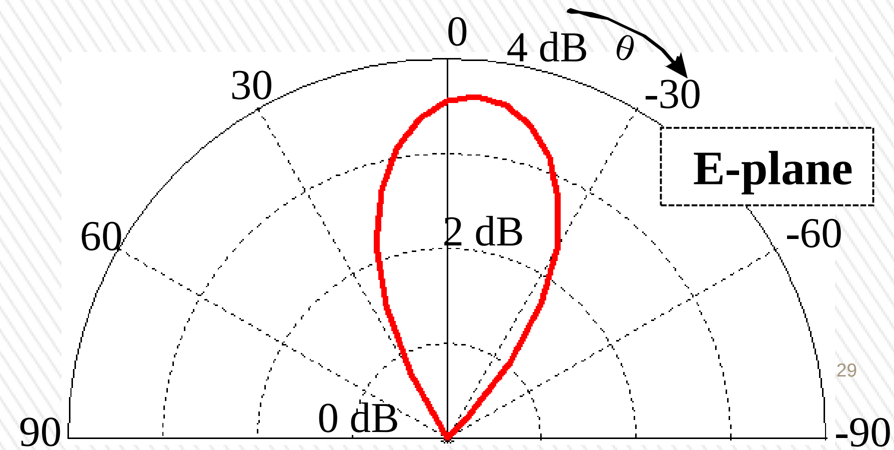
- Antenna dimensions minimization by exploiting *edge capacitive effects*
  - ⇒ λ/4 @ 2.45GHz is about 30 mm, indeed our solution reduce the dim. of >~20% (L_{opt}=25.45mm)
- Directivity undergoes *small variations* over the W range
  - ⇒ *suitable for resonant antenna optimization*
- *constant behavior* of the dipole radiation efficiency (~98%) when W is tuned

Flag-Shaped Printed dipole performance







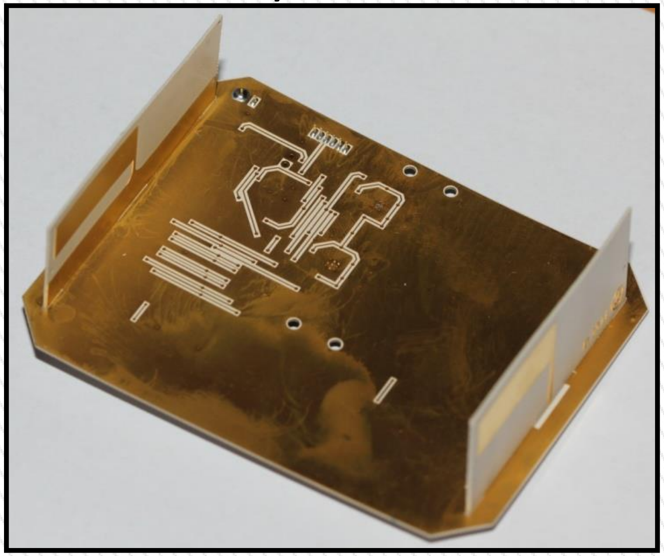


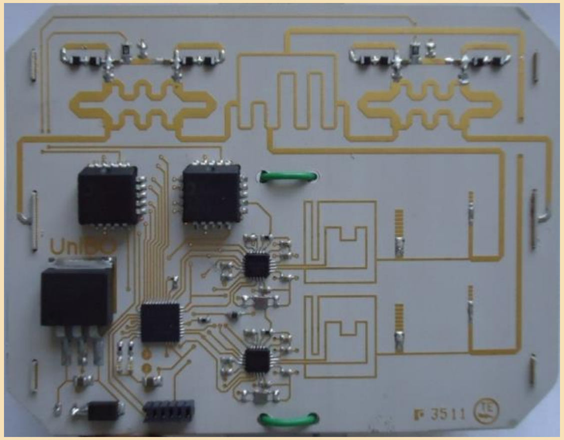
Antenna performance (H-plane)

- ***half-power beam-width*** is ~170°
- only 1.25 dB-directivity variation in the scanning zone (θ=±45°)
  - almost ***constant radiating behavior***
- **Radiation Efficiency 98%**

Integration with the reader

Entire system view





Radio and control chips mounted in the back-side

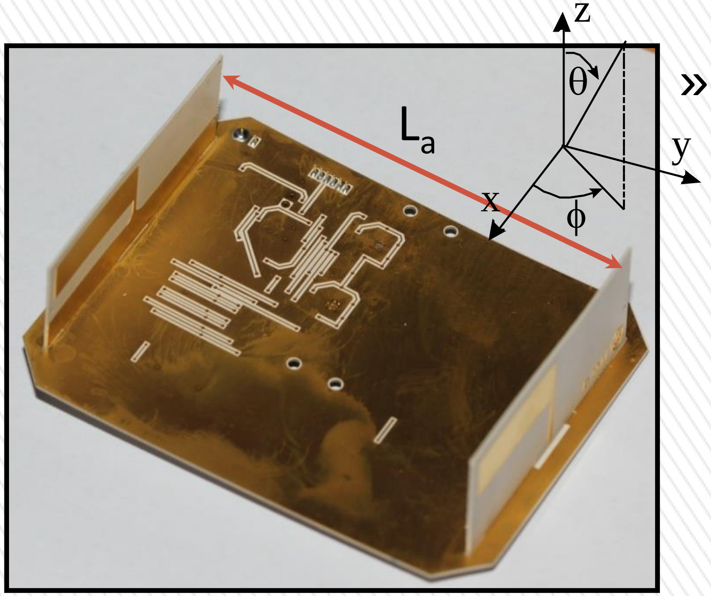
ad-hoc design in microstrip technology

» NOTE: printed dipoles and the microstrip subsystems are realized on the same substrate, Taconic RF-60A (0.635 mm-thick, $\varepsilon_r = 6.15$, tan$\delta = 0.0028$ @ 10 GHz)

» The commercial transceivers (for the Σ- and Δ-radios) have a maximum output power of 0 dBm @ 2.45 GHz.

» The dipoles exploit the ground plane to prevent from EM interference with the back-mounted components

Integration with the reader

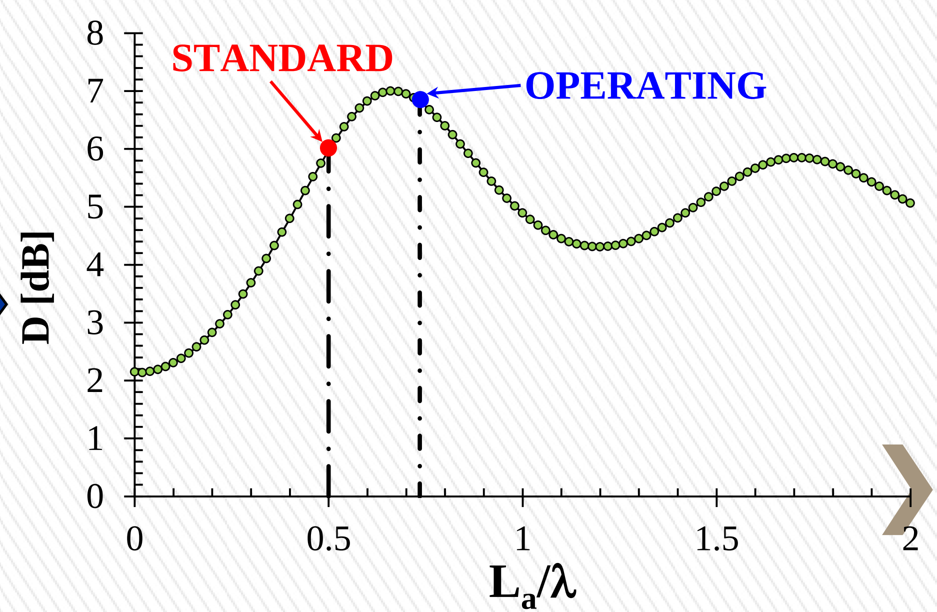


- The array phase centre distance chosen to minimize Σ directivity and side lobes, complying with circuit dimension constraints
  - Side lobes lead to inaccurate localization of lateral tagged objects
  - Good trade-off between low directive and back radiation

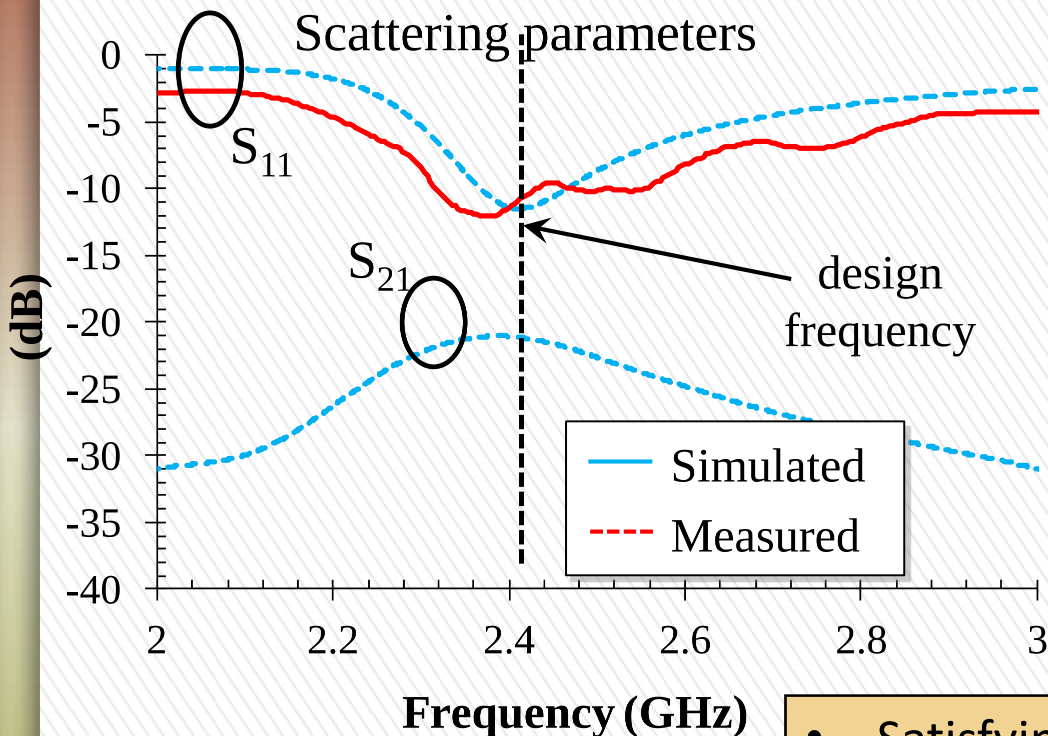
$$F_\Sigma(\theta,\phi) = \left| \cos\left(\pi \frac{L_a}{\lambda} \sin\theta \sin\phi \right) \right|$$

$$f(\theta,\phi) = f_0(\theta,\phi) \cdot F_\Sigma(\theta,\phi)$$

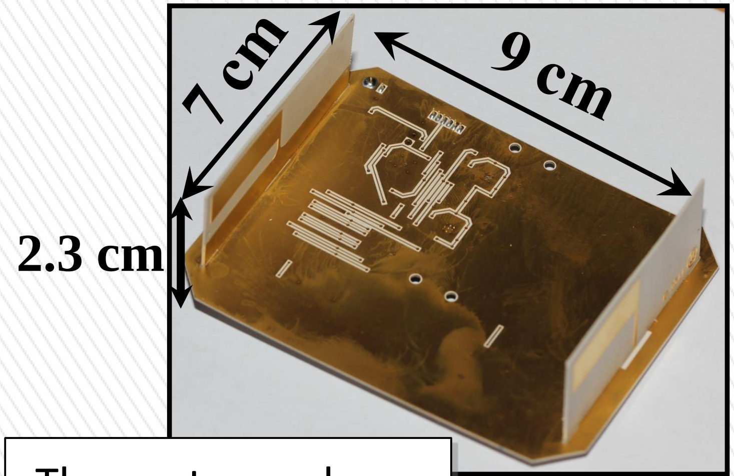
$$D = 4\pi \left(\int_{4\pi} f^2(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \right)^{-1}$$



Performance of the array integrated with the reader



Excellent agreement of S_{11}

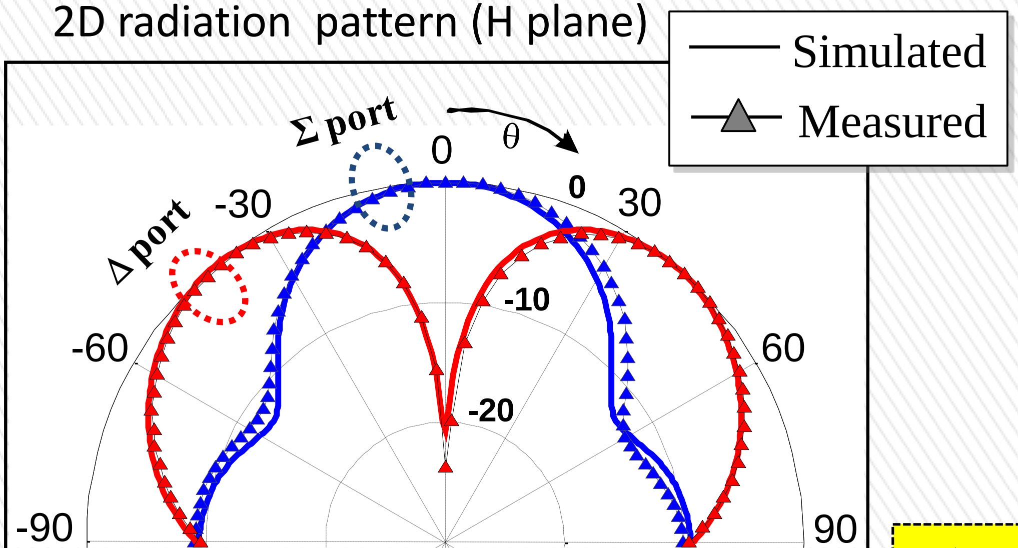


The system volume is 144 cm^3 only

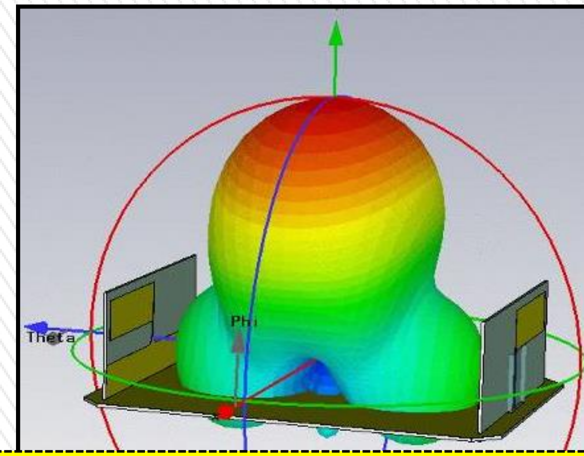
- Satisfying behavior of S_{11} is observed all over the band of interest around 2.45 GHz
- High decoupling between array elements
- Hand-held solution

Performance of the array integrated with the reader

2D radiation pattern (H plane)



Simulated 3D Σ radiation pattern



Δ- and Σ-patterns are measured *driven by* the rat-race and the phase-shifter

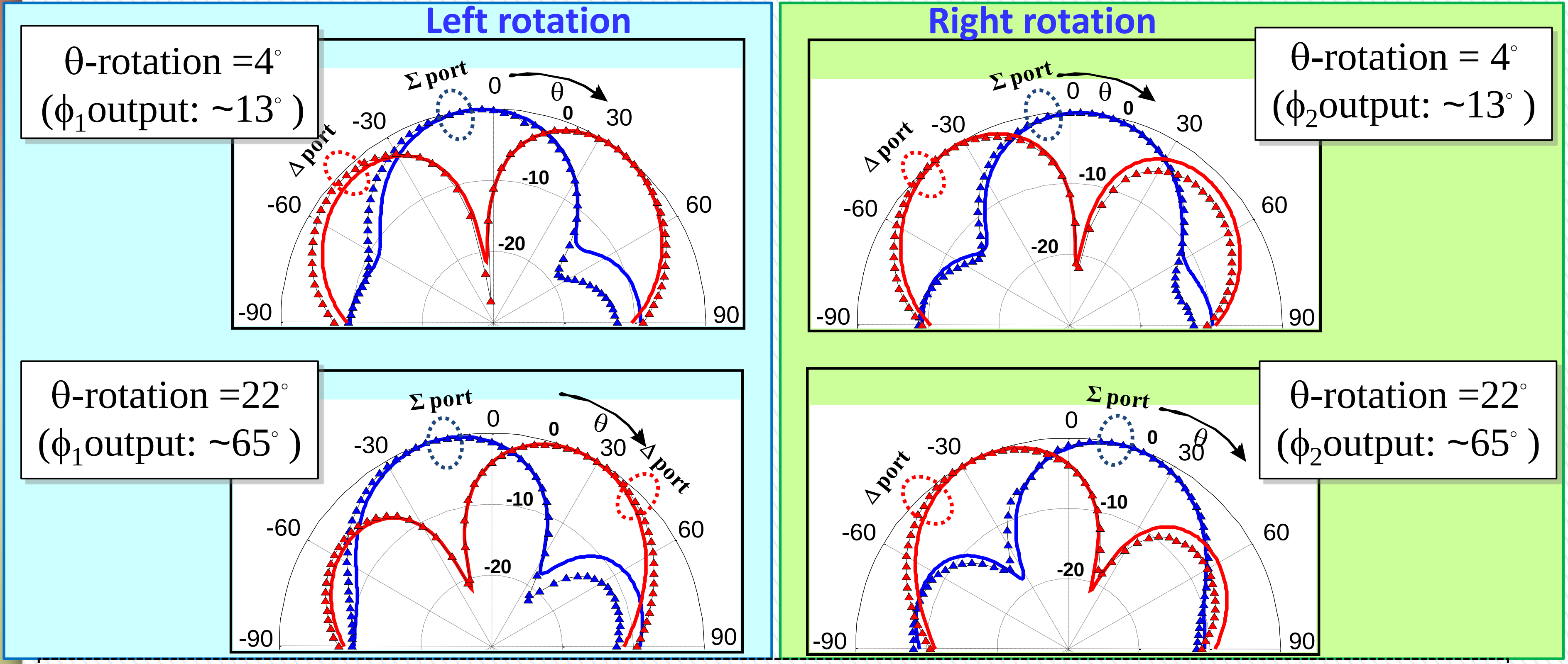
Performance @ 2.45 GHz

- Radiation Efficiency ⇒ 85%
- Front to Back Ratio ⇒ -15dB

Measure report

- Sharpness of Δ-pattern nulls are *20dB below* Σ-pattern maxima
- Σ- maxima and Δ- nulls perfectly *aligned*
- *reduced side-lobe* in Σ and Δ- pattern

Measured and predicted steering behavior of the reader



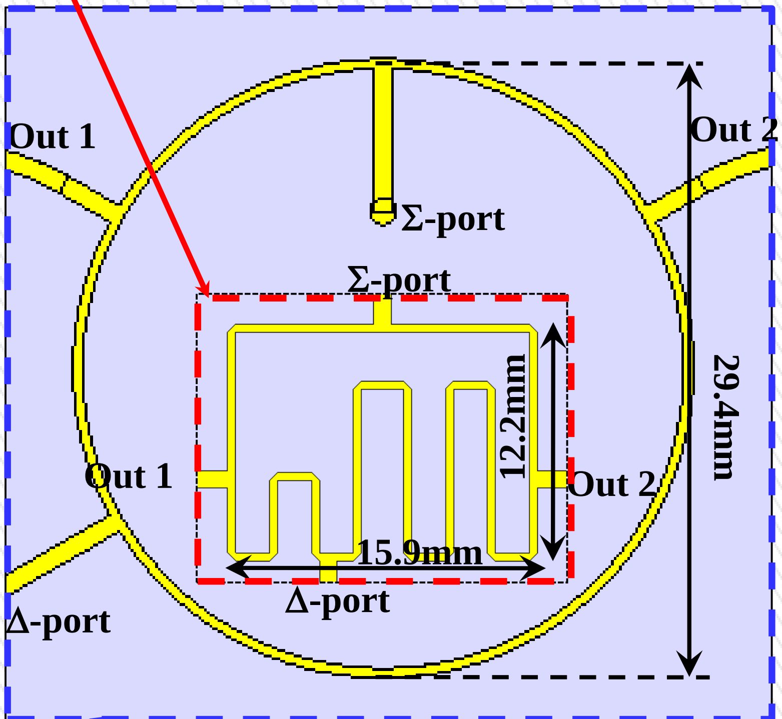
The use of low-directivity array guarantees good sharpness for any θ-direction

Excellent agreement is observed for each phase-shift of the array excitations: due to the accurate NL/EM co-design

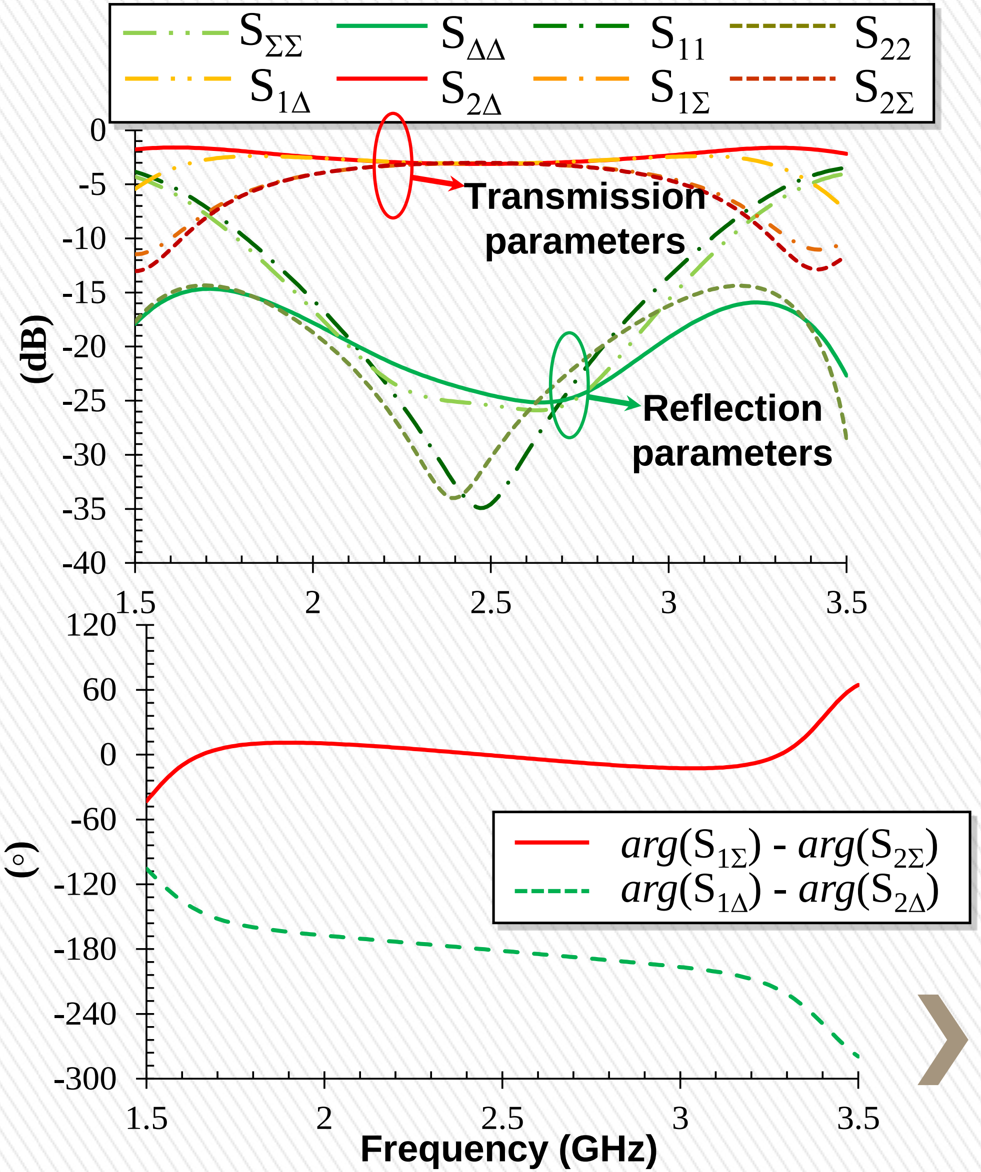
Beam steering range of ±45° corresponds to ±180° phase-shifts outputs

Miniaturized rat-race EM design

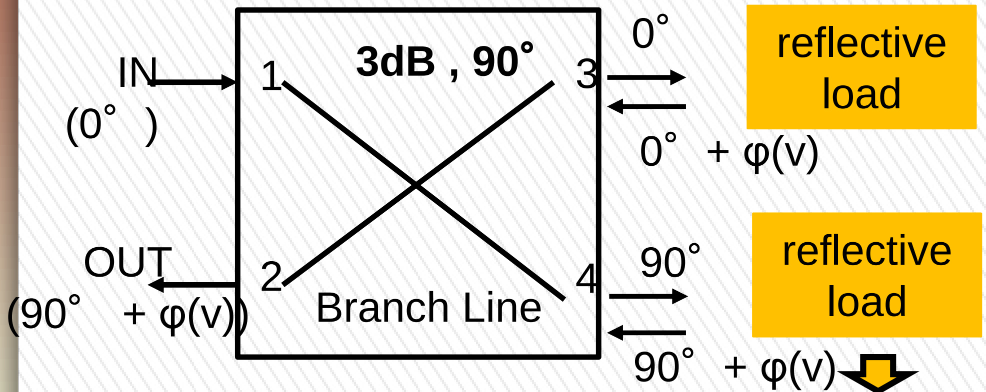
miniaturized topology
(200 mm²)
~ 75% occupied area reduction

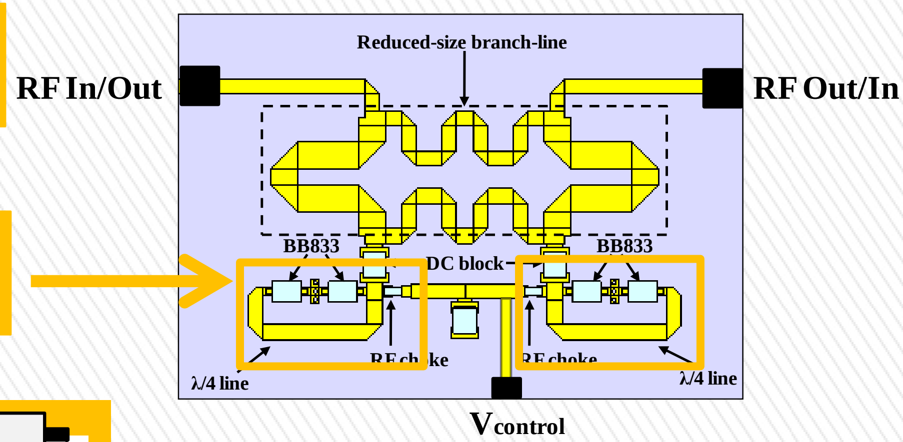


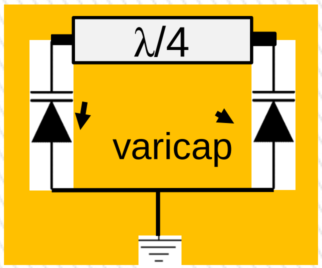
standard topology
(870 mm²)

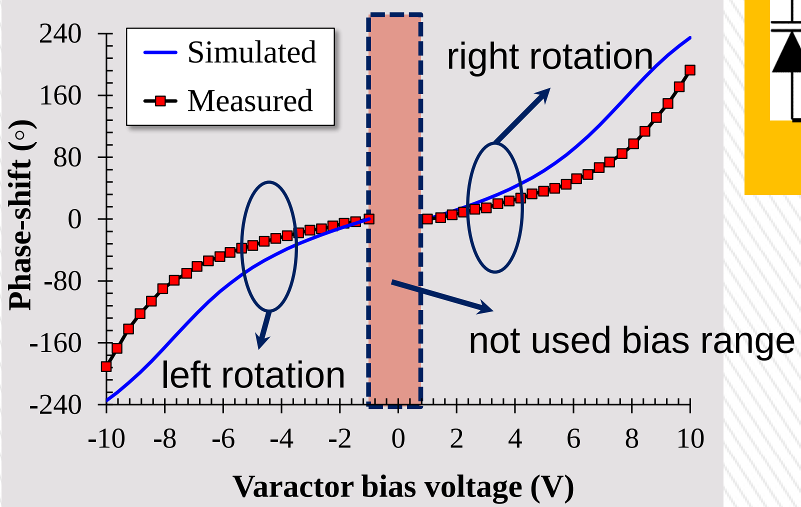


Nonlinear/EM design of the *reflection type* phase shifter

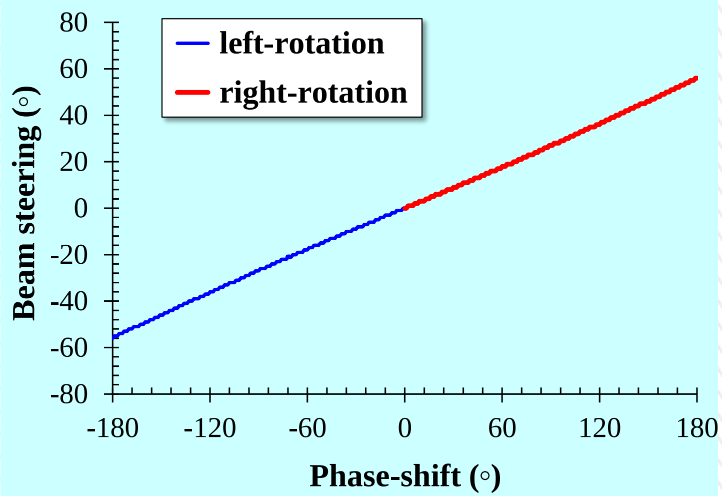








PS output phase

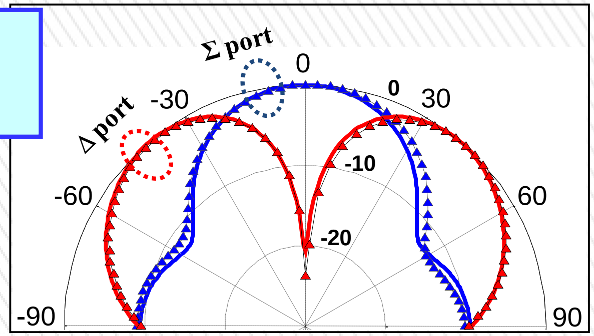


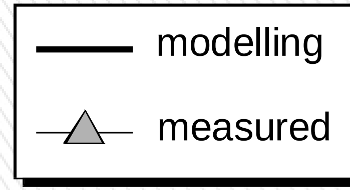
array beam steering

Measured and predicted Σ and Δ performance with PS

$\phi_1 - \phi_2 = 0°$

$V_1 = V_2 = 1V$

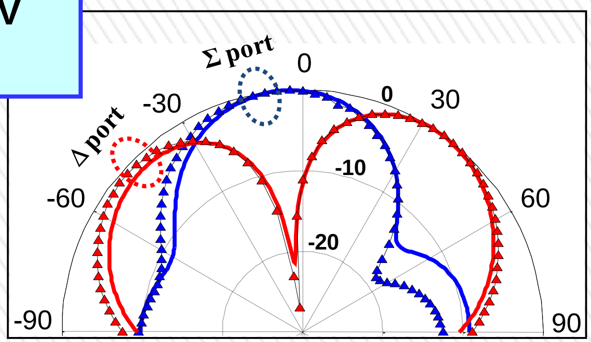




$\phi_1 - \phi_2 = -13°$

$V_1 = 3.48V$

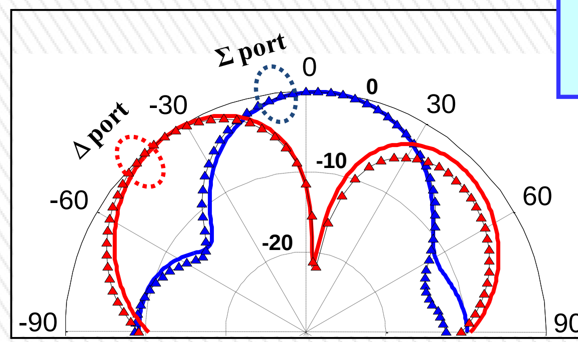
$V_2 = 1V$



$\phi_1 - \phi_2 = 13°$

$V_1 = 1V$

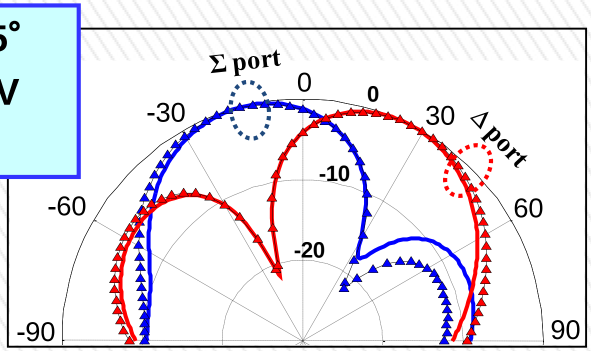
$V_2 = 3.48V$



$\phi_1 - \phi_2 = -65°$

$V_1 = 6.85V$

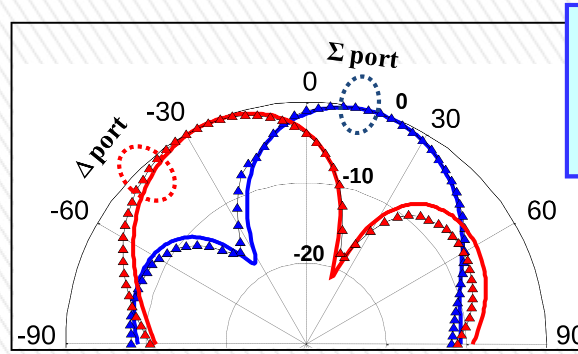
$V_2 = 1V$



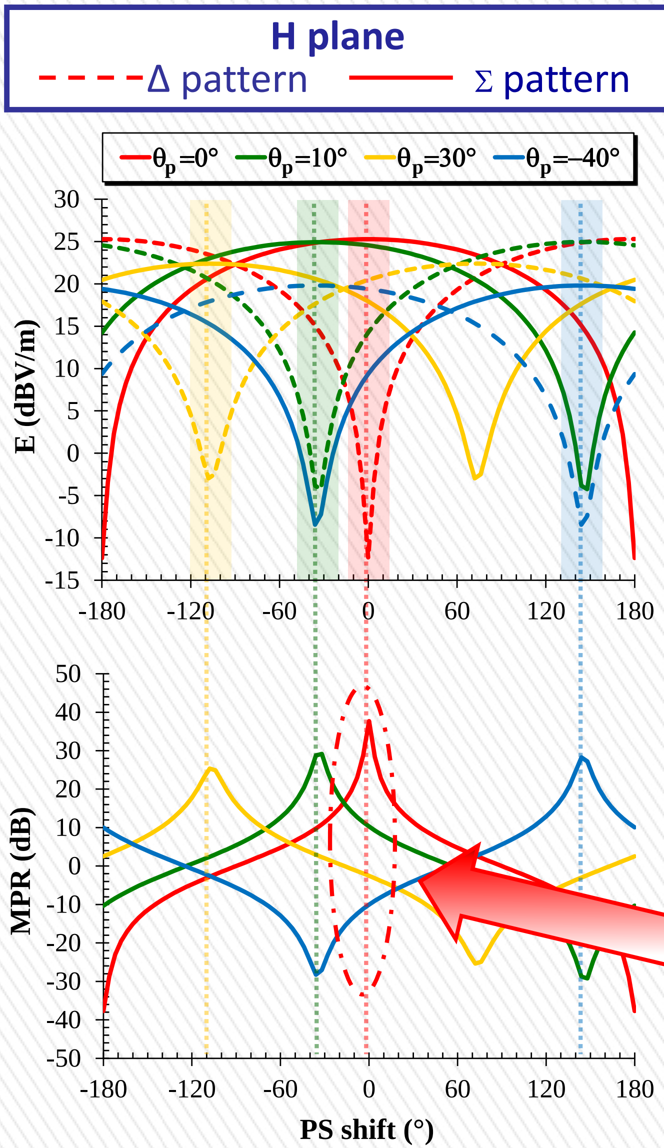
$\phi_1 - \phi_2 = 65°$

$V_1 = 1V$

$V_2 = 6.85V$



Object selection in 2 steps



***IDs ACQUISITION** (only the Σ radio is involved)*:

- RID points to the desired object
- Inquire for IDs

1

***SCANNING OPERATION** (Σ and Δ radios are involved)*

2

•Σ and Δ radios *cooperate* exploiting the scanning capabilities of the RID

•RID stores a list with IDs with the highest figure of merit:

MPR= Σ_{RSSI}[dB]- Δ_{RSSI}[dB]

•Select by electronic scanning :

Best centered MPR is the pointed object

(scanning zone (θ=±45°) swept in 40 steps, 1.5 ms each)

Data acquisition (2nd step)

- The Σ and Δ signals are suitably combined for each tag

$$\Sigma_{RSSI,i}[dB] = 10\log\left[RSSI_{\Sigma}(i)\frac{1}{\mu_{\Sigma}(i)\sigma_{\Sigma}(i)}\right];$$

$$\Delta_{RSSI,i}[dB] = 10\log\left[RSSI_{\Delta}(i)\frac{\sigma_{\Delta}(i)}{\mu_{\Delta}(i)}\right];$$

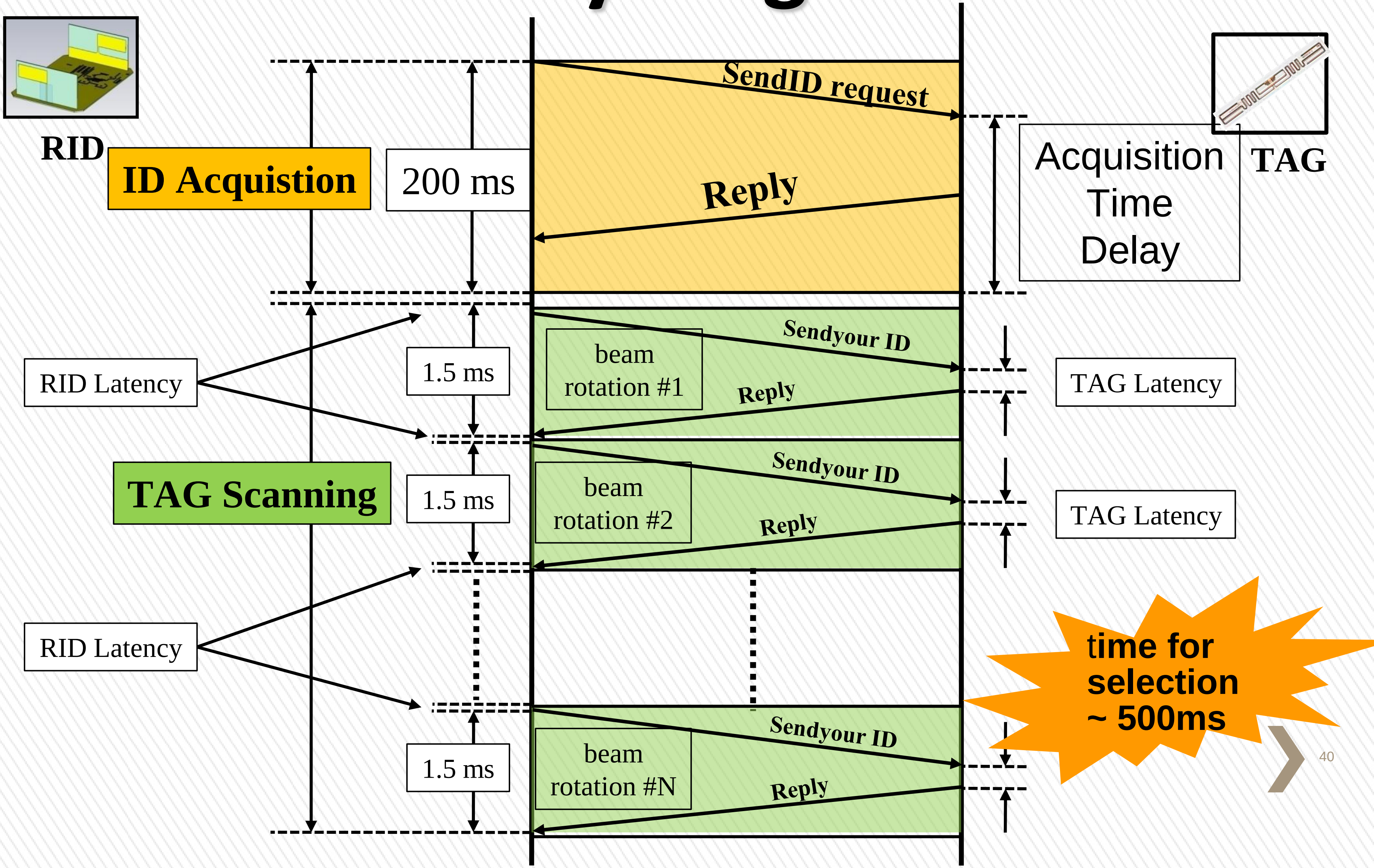
$$MPR_i = \Sigma_{RSSI,i}[dB] - \Delta_{RSSI,i}[dB] \quad ;$$

$$i = 1,\ldots,N_{tag}$$

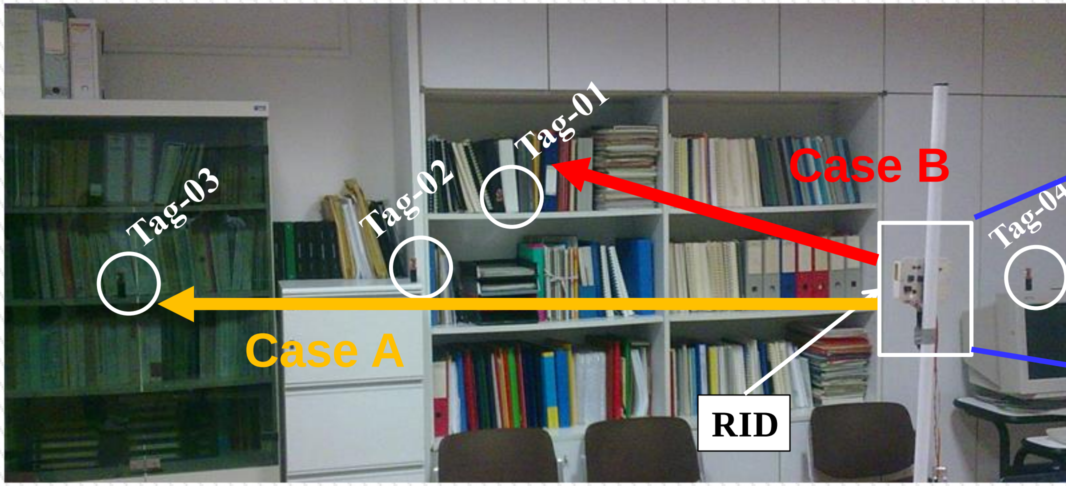
μ_{Σ}, μ_{Δ} and σ_{Σ}, σ_{Δ} are the mean values and standard deviations of the $RSSI_{\Sigma}$ and $RSSI_{\Delta}$ data (Received Signal Strength Indicator), respectively

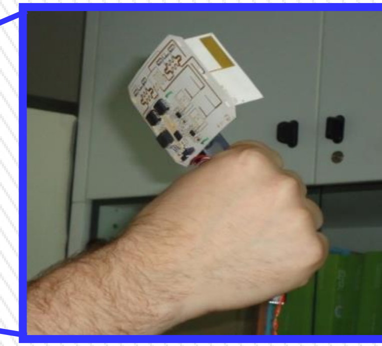
to compute the resulting Maximum Power Ratio (MPR)

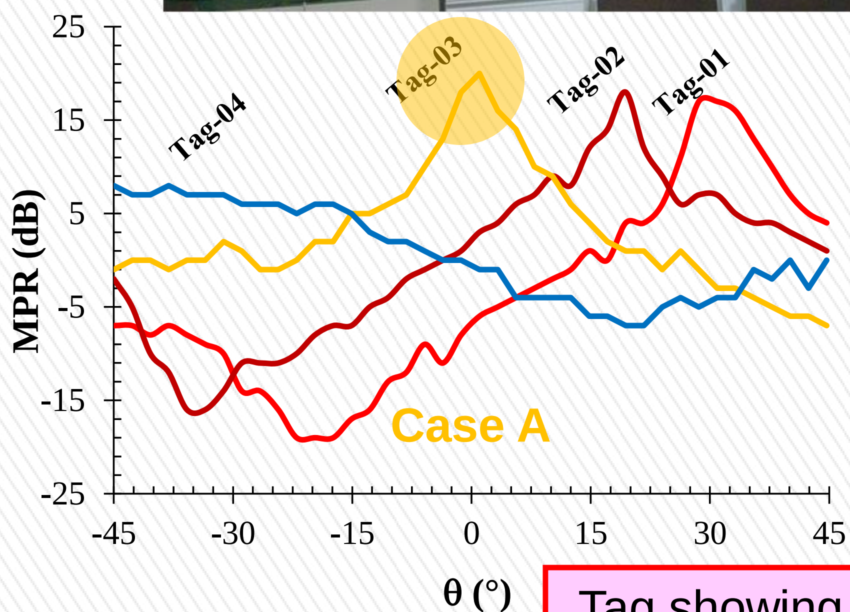
RID activity diagram

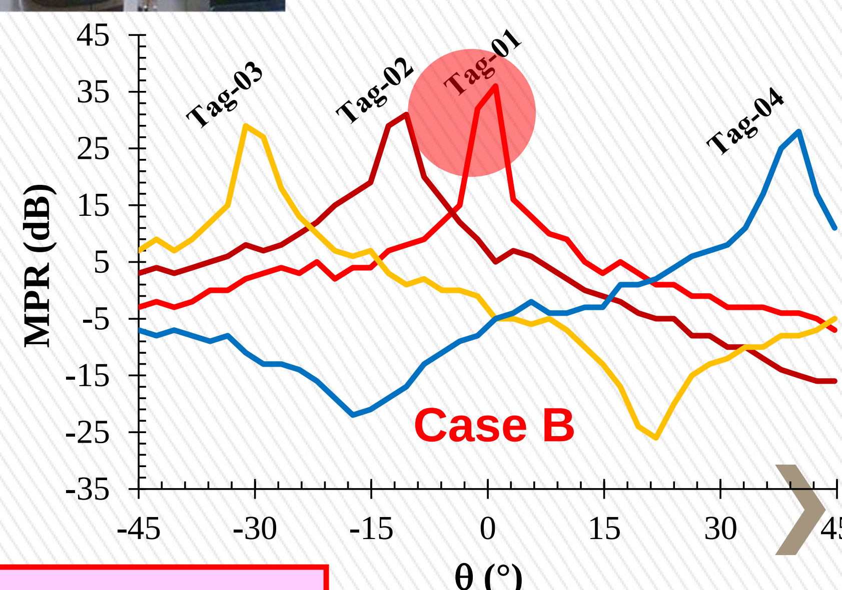


RID object selection in harsh EM environments





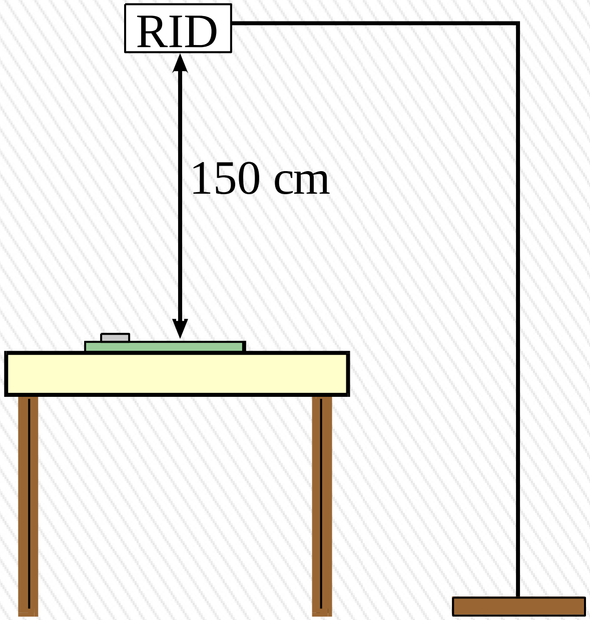


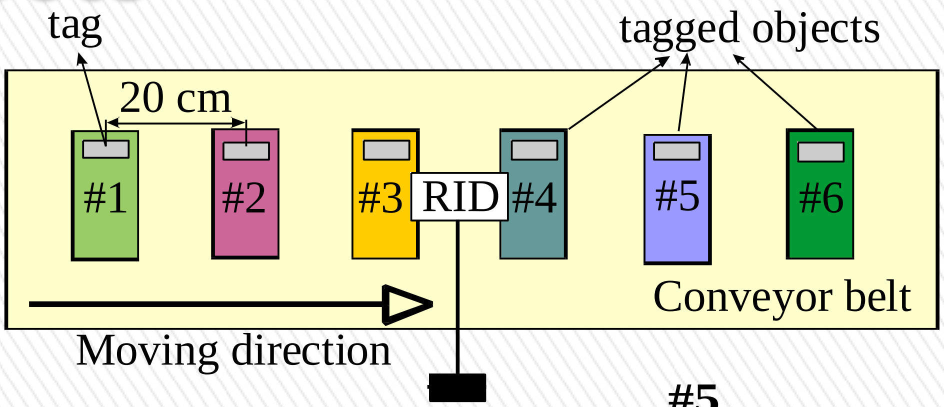


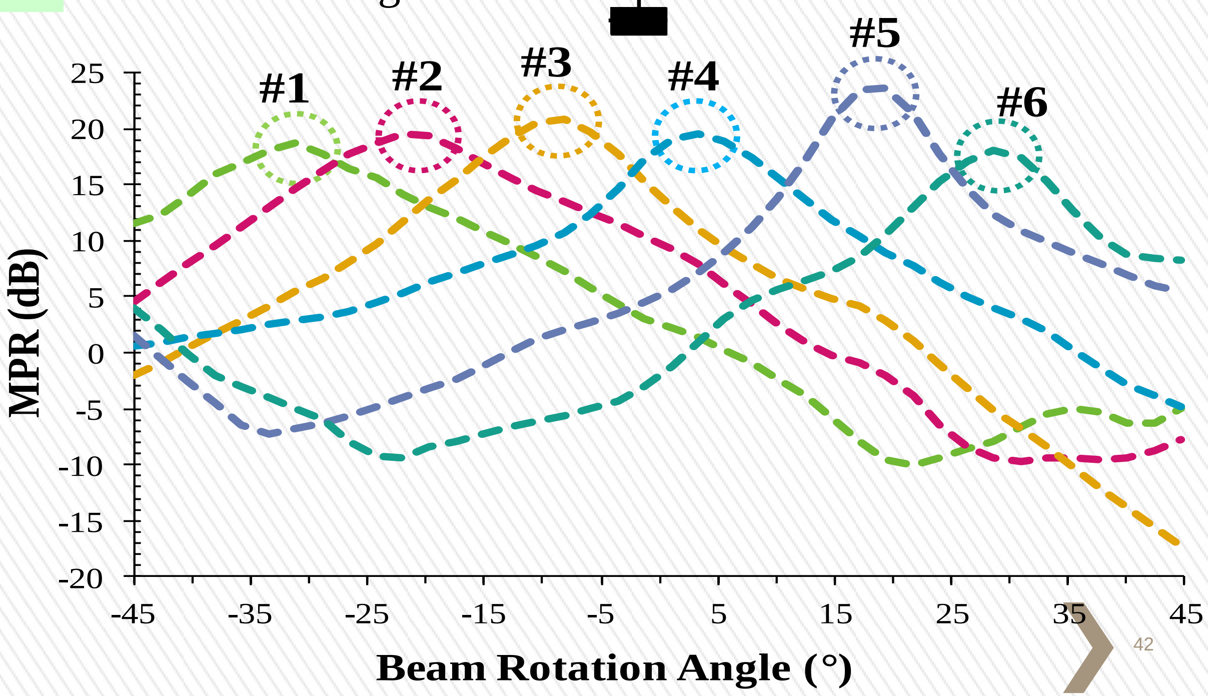
Tag showing the best MPR at a 0˚ -rotation angle is selected

RID sequence recording of moving objects

LABORATORY SET UP emulating a conveyor belt carrying 6 objects located 20-cm apart (typical speed 0.4 m/s)



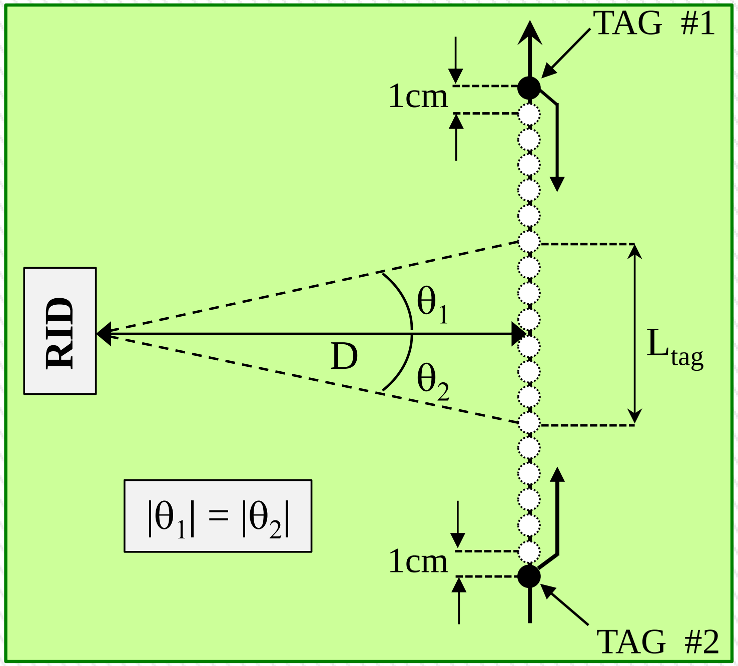




RID operation correctly completed in less than 500ms

RID sensitivity performance

» Figure of merit: minimum tags distance which guarantees unambiguous RID actions



$L_{tag} \in [2 \div 22]$ cm ; D = 1, 2, 3 m ; P_{tag} = 0 dBm

The angular position of the i-th tag, $\theta_i^{peak}; i = 1, 2$ is established as the best centered MPR

The sensitivity of the RID is defined as the minimum distance between tag #1 and tag #2 that allows $\Delta\theta = \theta_1^{peak} - \theta_2^{peak} > 0$

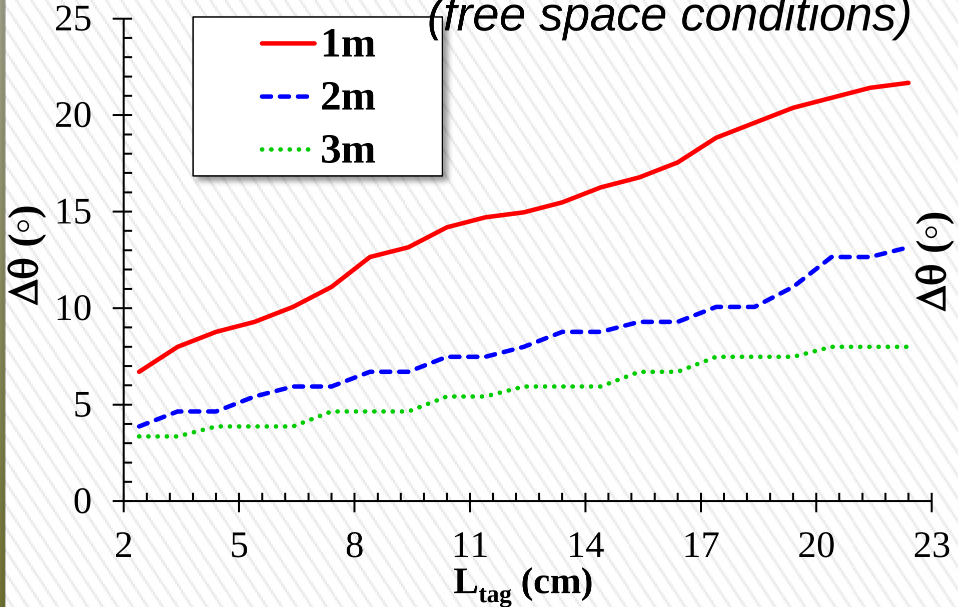
- A positive $\Delta\theta$ implies that RID is able to correctly receive the relative tags position with no squinting effects.
- A negative $\Delta\theta$ warns that tags positions have been swapped incorrectly.

RID sensitivity performance

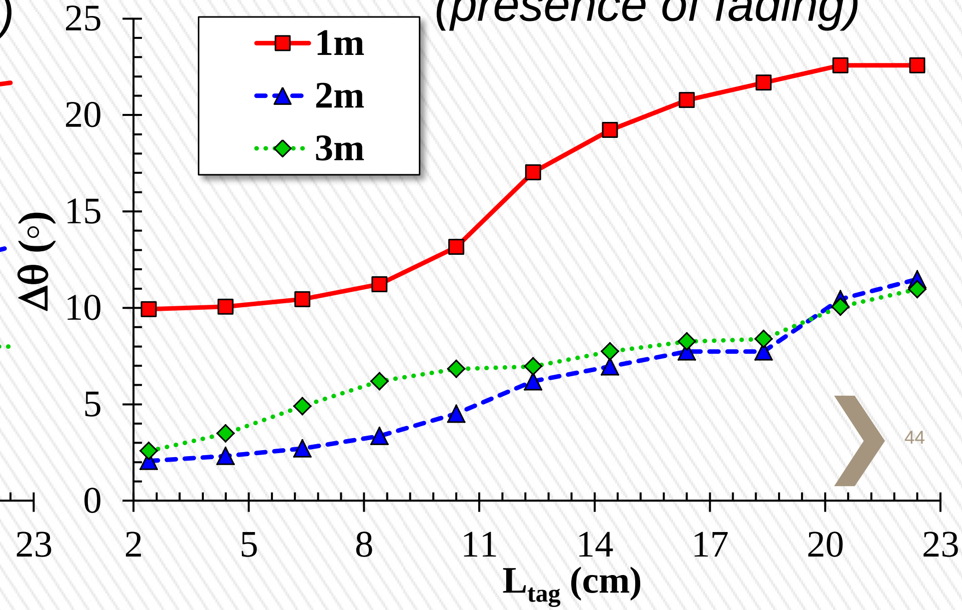
» 1 and 2-m distance measurements in good agreement with prediction (the LOS link is almost free from multipath fading effects)

» For a 3-m distance Δθ is still positive (even for the lower tag-to-tag distances), but significant deviation from prediction is observed ➡ strong impact of the channel effects on measurements

predicted
(free space conditions)

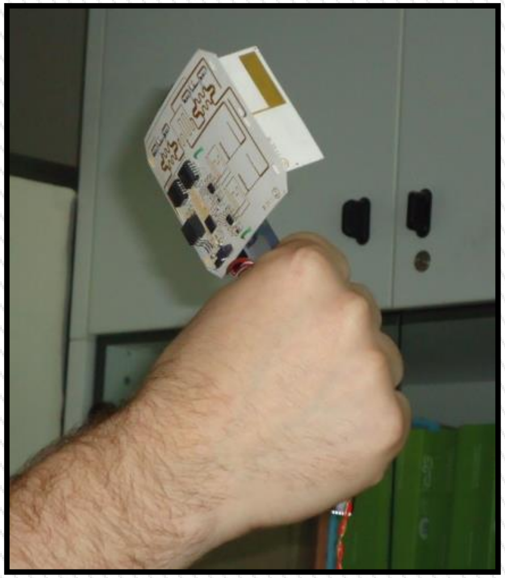


measured
(presence of fading)



Conclusions

» The RID is a new reader solution @ 2.45 GHz
  > low-cost
  > low-power (88 mW for the last operation, mainly due to the adopted DAC)
  > hand-held (weight less than 200 gr.)



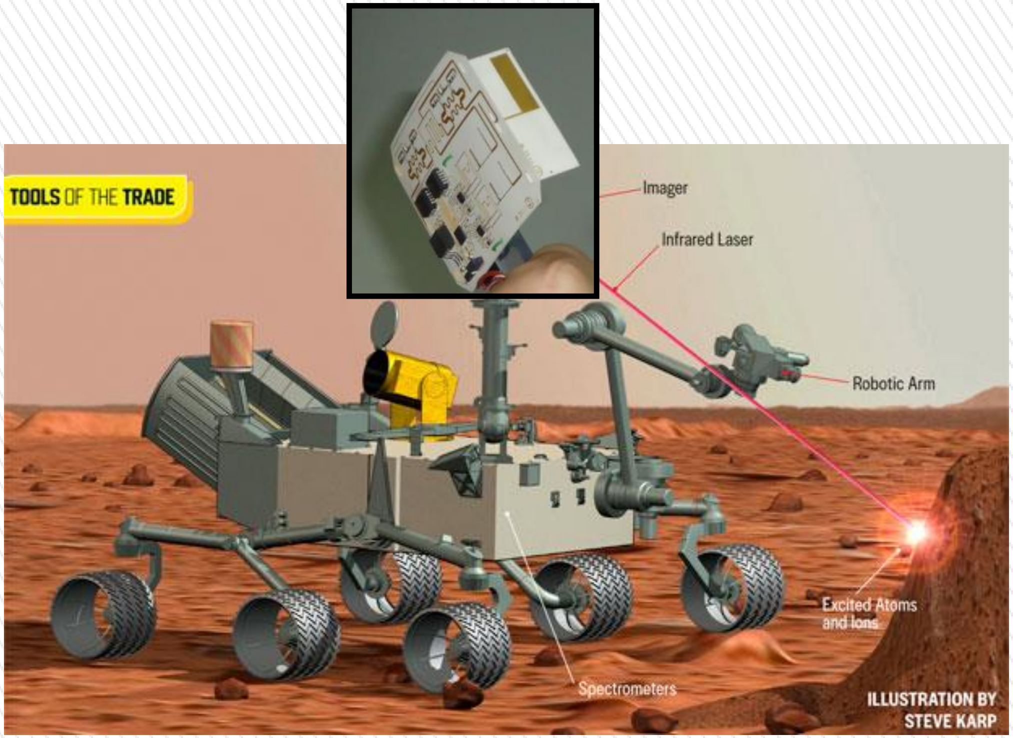
» Standard RFID reader activities integrated with electronic scanning capabilities

» Taking advantage of the monopulse RADAR principle, the RID is an effective solution to overcome reading failures, due to multipath effects typical of indoor spaces, *WITHOUT* time-consuming recovery operations scanning capabilities

Conclusions

- » Robust operation in the presence of closely-spaced objects ***fixed*** and ***moving***.
- » Smart RFID reader operating in the microwave range able:
- » Can be combined with power sources to selectively activate sensors/microsystems

Implementation of the ***SMART-SPACE*** concept, RID may exchange, retrieve and update information with selected or detected objects



WPT-related projects

ARROWHEAD

ARTEMIS JU SP3 Arrowhead European Project. Available

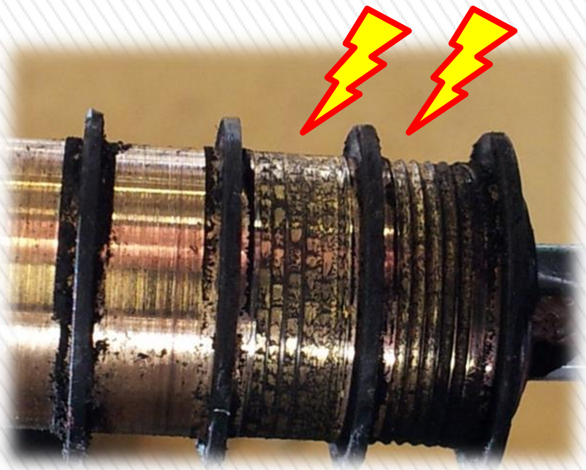
http://www.arrowhead.eu/

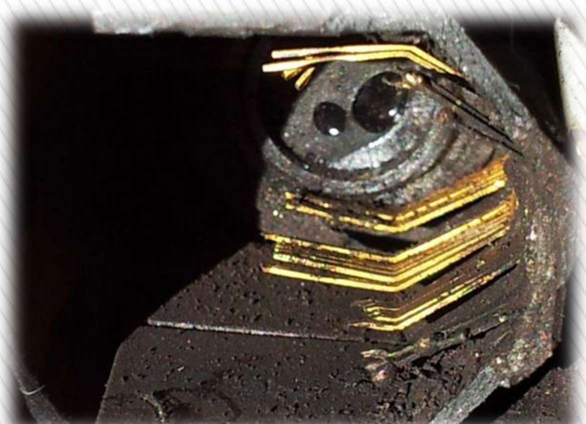
eit Knowledge & Innovation Community

EIT ICT Labs

kW energy transfer to rotary joints

Slip rings



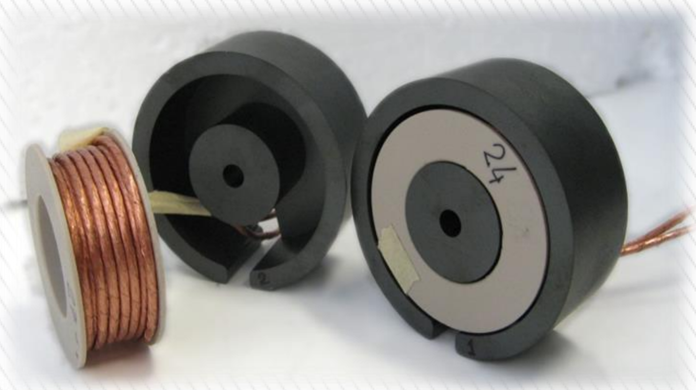


Energy transfer with cables

1.3 kW Contactless Energy transfer

» Requirements:

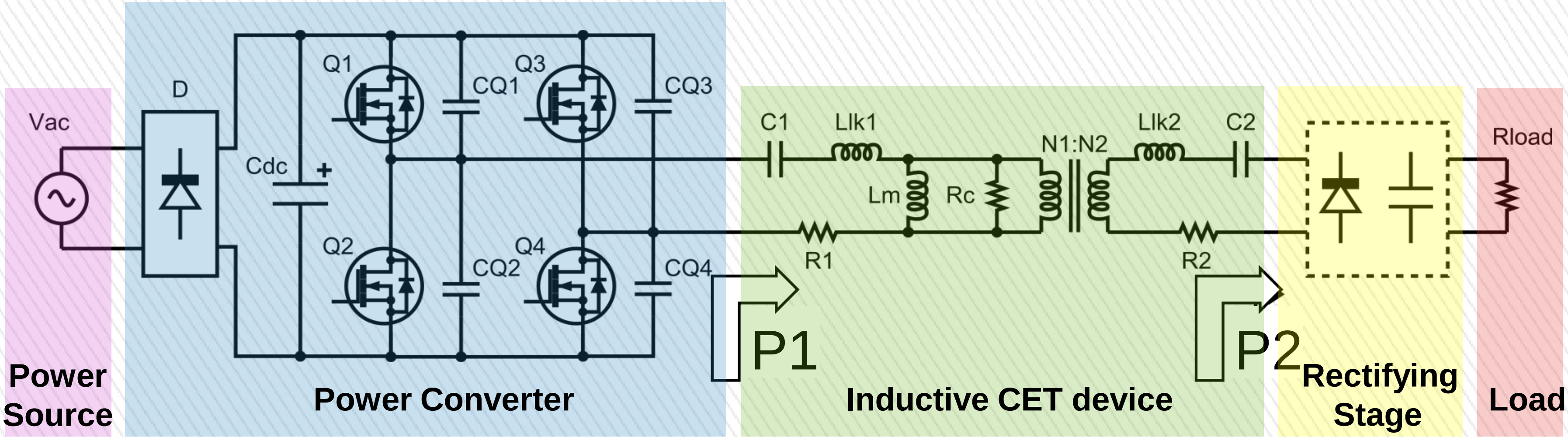
- > Output voltage = 230 Vac
- > Power rating= 1.3 kW
- > Air gap = 0.6 mm
- > Temperature = [20 – 80] ° C
- > Efficiency > 90 %

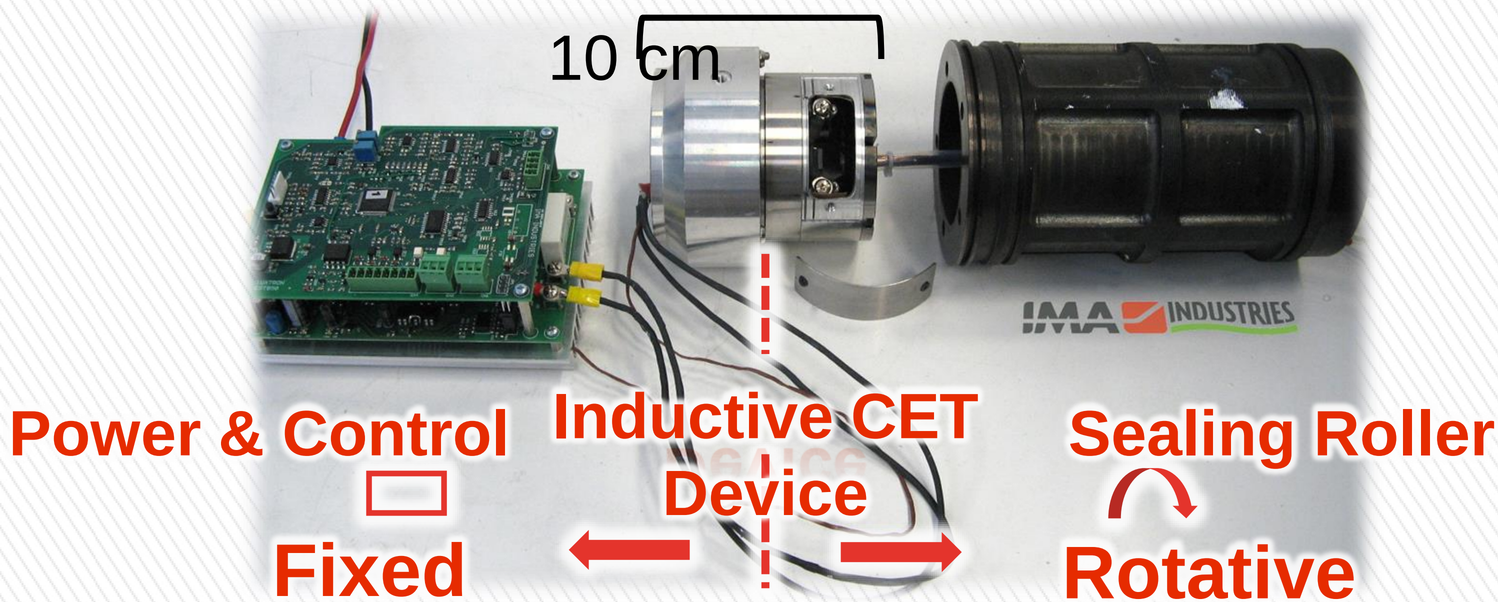


- Limitations:
  - Frequency (~ 50 kHz)
  - Winding and core losses (~ 30 W)
  - Core's saturation (~ 0,5 T)
  - Temperature (~ 100 °C)
  - Electro-magnetic compatibility (EMC)
  - Available radial space (35 mm)

- Trade-offs:
  - Wire (section, strands)
  - Turns
  - Frequency tuning
  - Ferrite type
  - Compensation schemes
  - Core size

1.3 kW Contactless Energy transfer





"A 1-kW contactless energy transfer system based on a rotary transformer for sealing rollers," *IEEE Trans. Ind. Electron.*, 2014

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