SMART BEAMING OF RFID READER FOR DATA AND POWER TRANSFER

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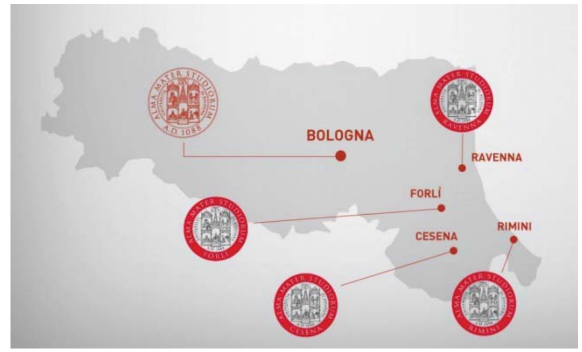
UNIVERSITY OF BOLOGNA

UNIVERSITY OF BOLOGNA: THE CAMPUSES

Campuses



- BOLOGNA
- CESENA
- FORLÌ
- RAVENNA
- RIMINI
- **BUENOS AIRES**

UNIVERSITY OF BOLOGNA: THE STUDIUM FROM OVER 900 YEARS

1088	1988
STUDIUM IN BOLOGNA	MAGNA CHARTA UNIVERSITATUM
IT IS THE OLDEST UNIVERSITY IN THE WESTERN WORLD	**CONFIRMS THE ESSENTIAL ROLE OF THE UNIVERSITY IN CONTEMPORARY SOCIETY**

ARCHIGINNASIO

ANATOMICAL THEATRE 1653

BOLOGNA AND GUGLIELMO MARCONI

Fondazione Guglielmo Marconi

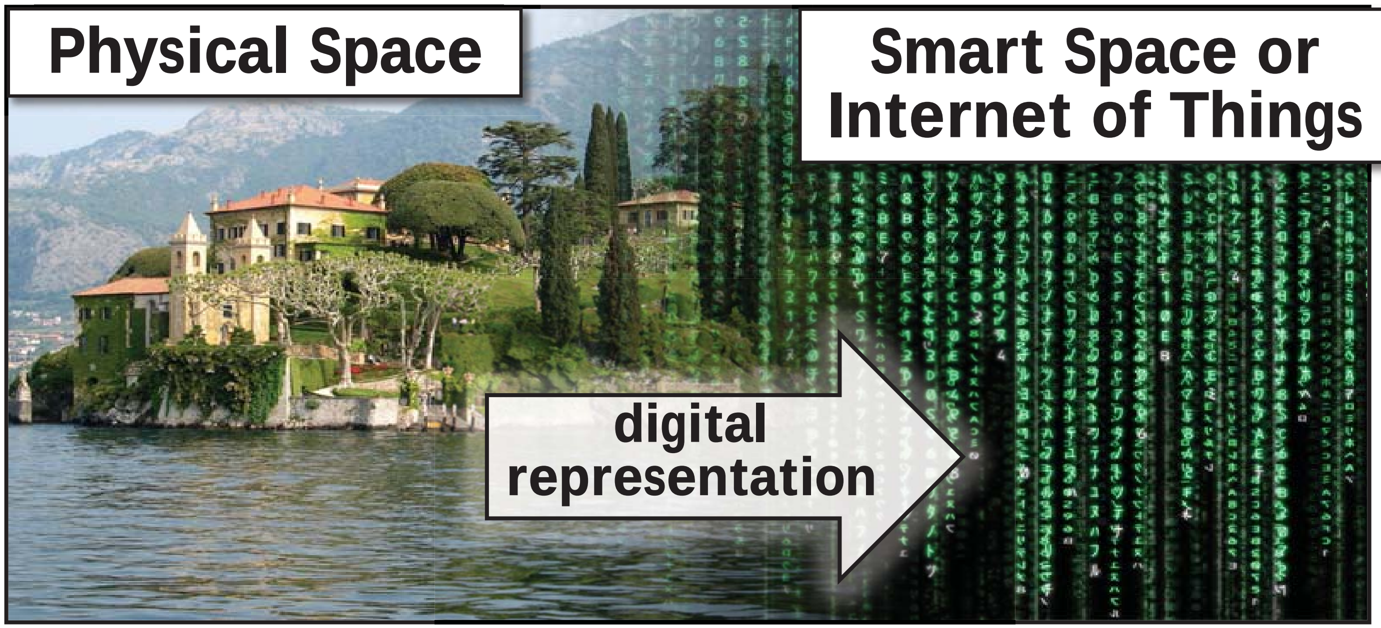
VILLA GRIFFONE

SUMMARY

- Introduction & background of the IoT paradigm
- **The need**: zero-power localization, identification, sensing
- ***RX side:*** sensor nodes ***need*** for energy collection from ***environmental*** and/or ***intentional*** RF sources: RECTifyng antENNAs (RECTENNAs)
- ***TX side/RFID reader***: ***need*** for agile radiating systems
  - ***Readers*** augmented with ***localization*** and ***selection capabilities***
  - Reader with monopulse RADAR capabilities
  - ***Time-modulated arrays (TMAs)***: a highly reconfigurable family of radiating systems. ***Design*** by nonlinear CAD and EM simulation
  - Real-time exploitation of TMA for multi-frequency beam-forming for ***Smart Wireless Power Transmission***
- Conclusions

THE VISION: “INTERNET OF THINGS”

- “Map” the physical world into the internet space
  Physical World Web



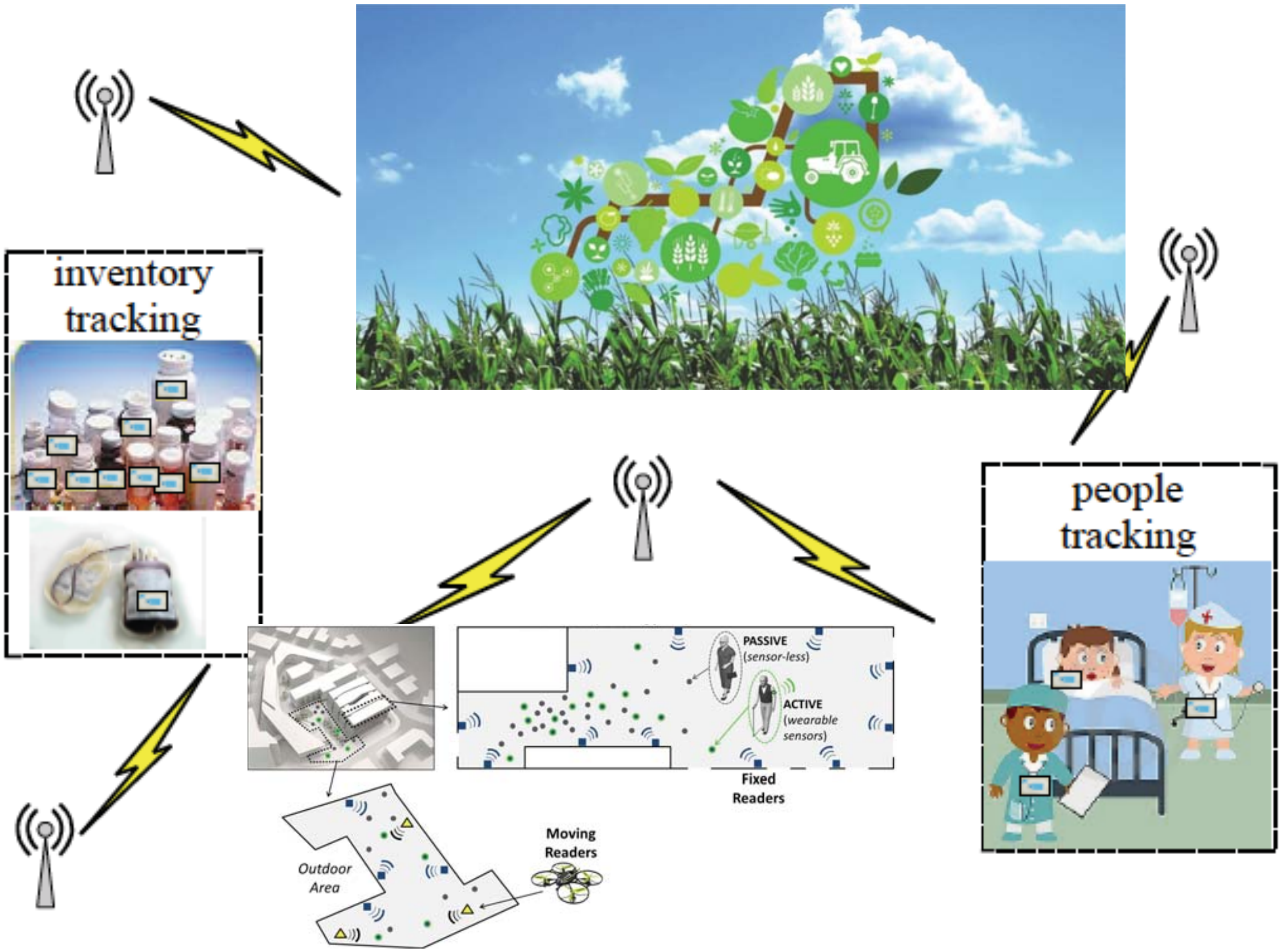
Expected >50 billion devices!

➢ ***Ambient intelligence***: almost unlimited applications

INTERNET OF THINGS APPLICATIONS

indoor and outdoor crowded areas with movable sensor-less and sensor-enabled objects.

mobile and fixed wireless nodes are spread out through the scenario to provide energy for multi-parameter monitoring



INTERNET OF THINGS: TECHNOLOGY REQUIREMENTS

- Devices embedded inside objects
  - Extremely *low cost*
  - Energy autonomous (*energy harvesting, low consumption*)
  - Eco-compatible (disposable)
  - Sub-meter *localizable* sensing capability

Convergence of Radio Frequency IDentification (RFID) and Real-time Locating Systems (RTLS)

(>6 billions new market opportunities in 2022*)

- Zero-power communication and localization

(*) IDTechEx “Real Time Locating Systems 2012-2022” www.IDTechEx.com/RTLS

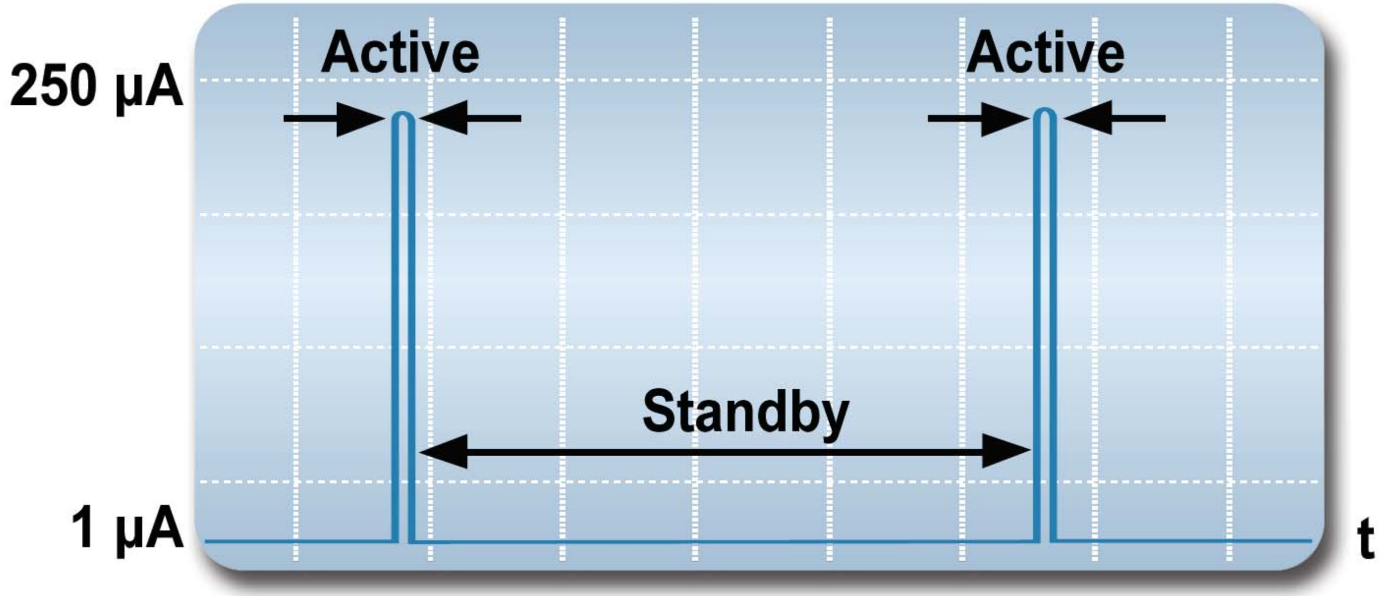
P. Harrop and R. Das, "Wireless Sensor Networks 2011-2021: The new market for Ubiquitous Sensor Networks (USN)", www.IDTechEx.com

P. Harrop and R. Das, “Energy Harvesting and Storage for Electronic Devices 2011-2021”, www.IDTechEx.com

RF ENERGY HARVESTING

NEED FOR LOW ENERGY

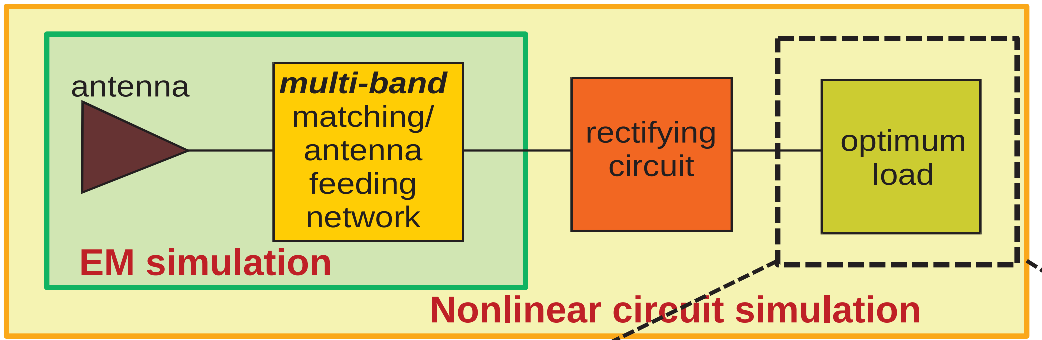
- Many applications can be supported by small amounts of power (*from a few μW to a few hundreds of μW*),



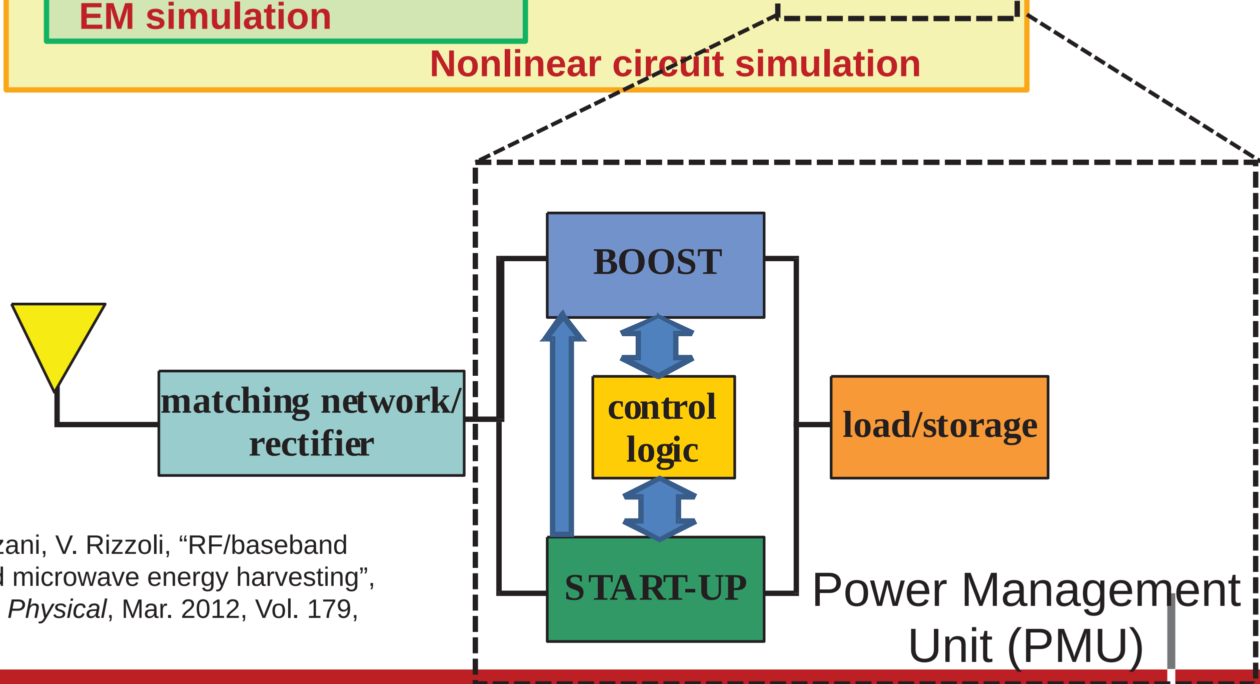
ultra-low power microcontrollers and sensors requiring power consumption few times per day

RECTENNA

- RECtifying anTENNA (RECTENNA) is the subsystem devoted to receive the RF power and rectify it to DC
  - 1st level design



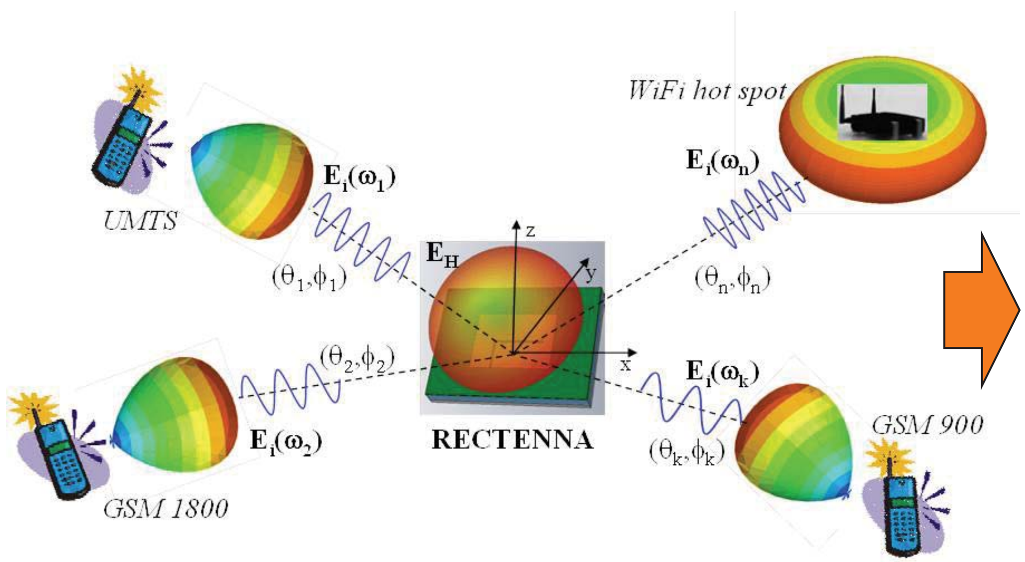
  - 2nd level design



A. Costanzo, A. Romani, D. Masotti, N. Arbizzani, V. Rizzoli, "RF/baseband co-design of switching receivers for multiband microwave energy harvesting", *Elsevier Journal on Sensors and Actuators A: Physical*, Mar. 2012, Vol. 179, No. 1, pp. 158-168

RECTENNA FOR ENERGY HARVESTING

- RECTENNA for Energy Harvesting: exploits ***environmental*** RF sources



collected power in the low μW range

not deterministically predictable, considering:

i. Channel fading
ii. antennas misalignments
iii. Antenna mis-polarizazion

- These systems could be more suitable for “RF upon request” applications

A. Costanzo, M. Dionigi, D. Masotti, M Mongiardo, G. Monti, L. Tarricone, R. Sorrentino, "Electromagnetic Energy Harvesting and Wireless Power Transmission: A Unified Approach," Proceedings of the IEEE , vol.102, no.11, pp.1692,1711, Nov. 2014

RECTENNA FOR WPT

- RECTENNA for Wireless Power Transfer: exploits ***intentional and dedicated*** RF sources (***“Energy showers”***)

collected power in the high μW range (considering realistic scenarios)

Italian PROJECT PRIN 2011

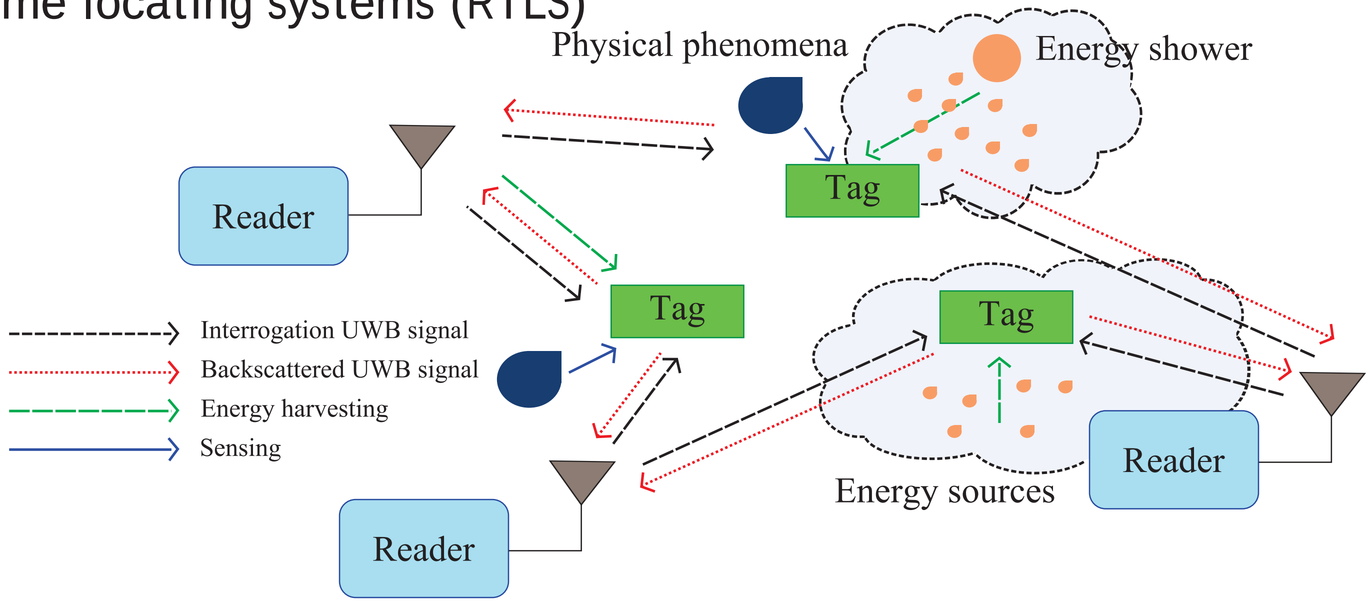
http://www.greentags.eu

N. Decarli, et al., "The GRETA architecture for energy efficient radio identification and localization," 2015 International EURASIP Workshop on RFID Technology (EURFID), pp.1-8, 22-23 Oct. 2015

GRETA OBJECTIVES

Integration of the concepts of

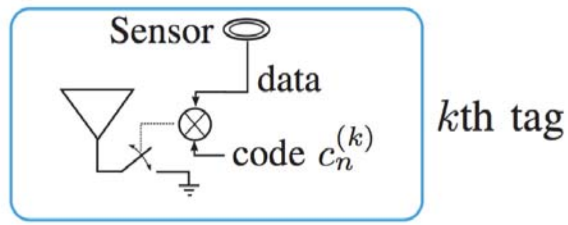
- Radiofrequency identification (RFID)
- Wireless sensor networks (WSN)
- Real time locating systems (RTLS)



GREen TAgs and sensors with ultra-wide-band Identification and localization capabilities

UWB-RFID: MAIN ISSUES

The GRETA tag exploits the UWB backscattering mechanism



- ***The poor link budget***

Due to the two-hop communication scheme and the standard carrier frequency, the received signal backscattered by the tag is very weak.

- ***The multi-tag management***

When adopting UWB backscatter communication, no anti-collision protocol can be implemented due to the extremely simple tag front-end and the absence of any receiver and processing unit at tag side.

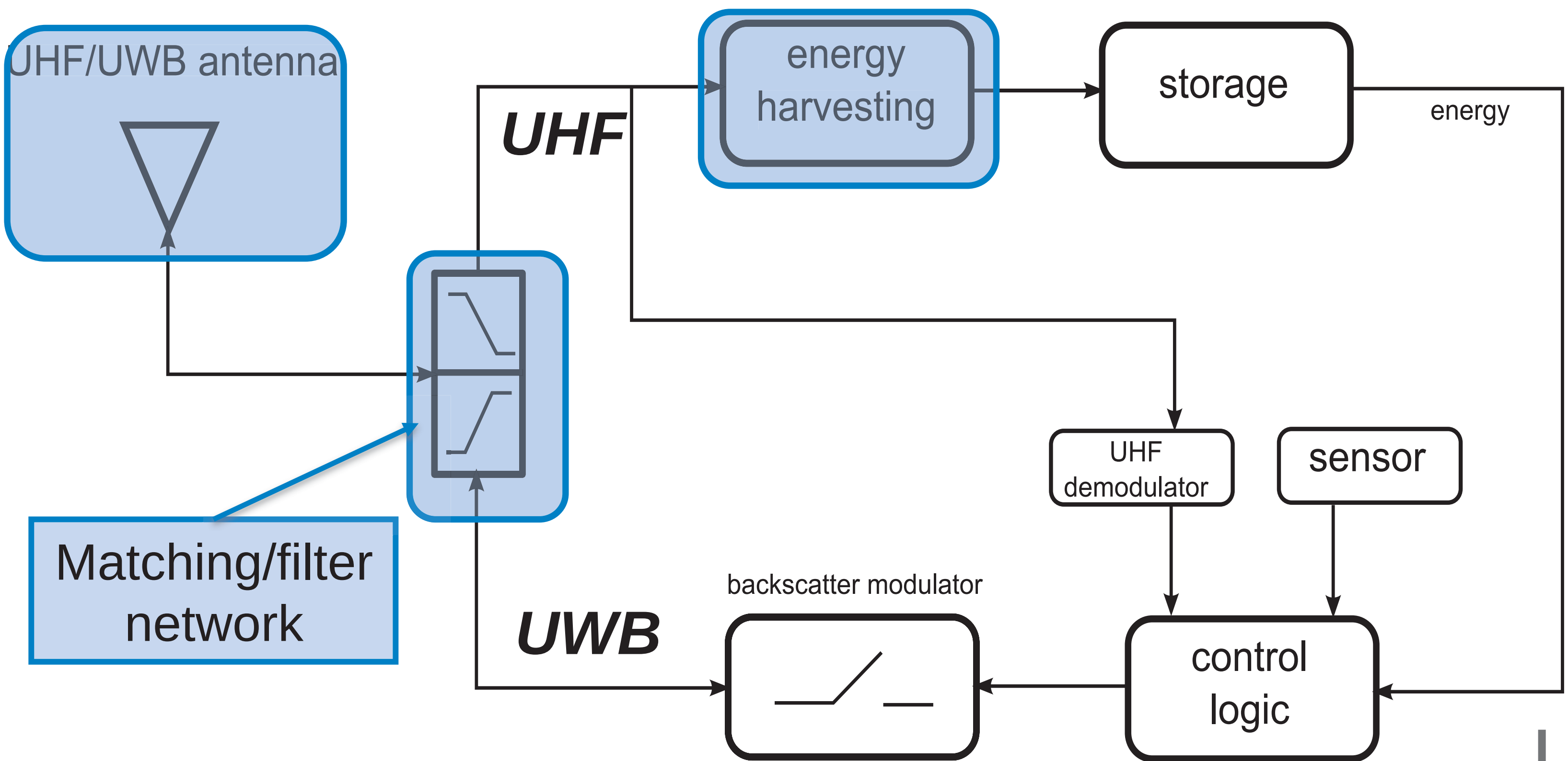
- ***The energy-related aspects***

The circuitry at tag side (UWB switch, control logic and sensors) must be properly powered so energy-harvesting techniques have to be considered.

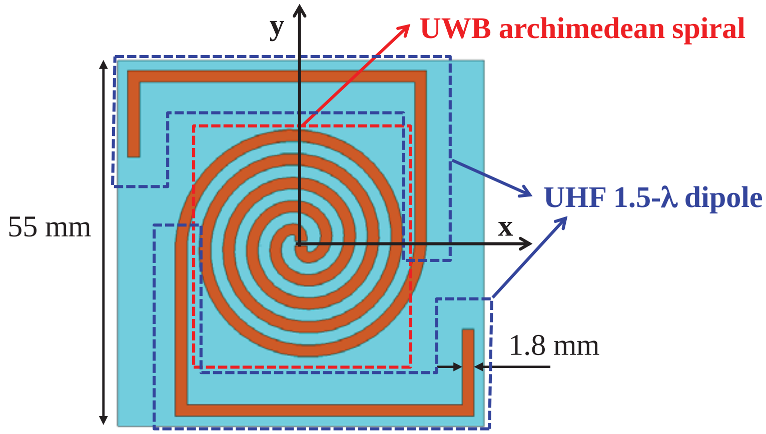
Joint adoption of UWB and UHF signaling

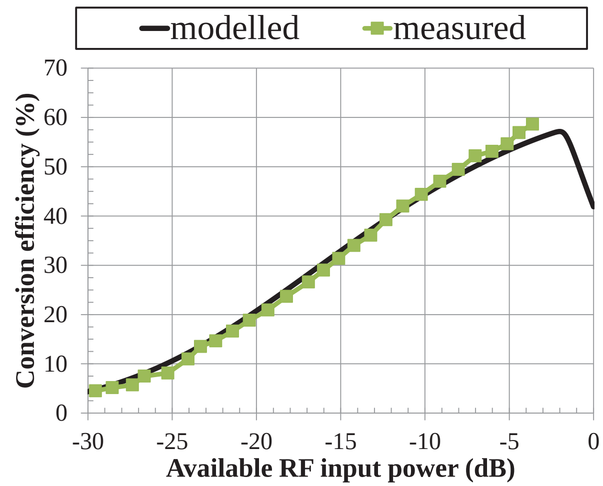
UWB/UHF STAND-ALONE TAG

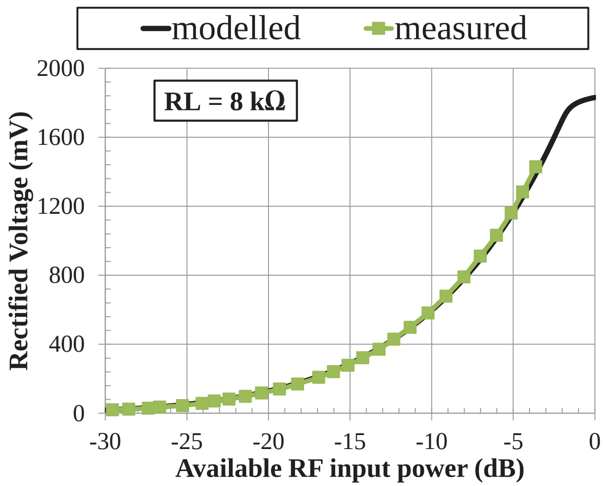
UWB (3.1÷5.6 GHZ) for communication (Tag ID, sensor data) and localization
Energy-harvesting and synchronization through the UHF (868 MHZ) link



UWB STAND-ALONE TAG







M. Fantuzzi, D. Masotti and A. Costanzo, "A Novel Integrated UWB–UHF One-Port Antenna for Localization and Energy Harvesting," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 9, pp. 3839-3848, Sept. 2015.

RECTENNA FOR EH

- Rectenna for EH requirements:

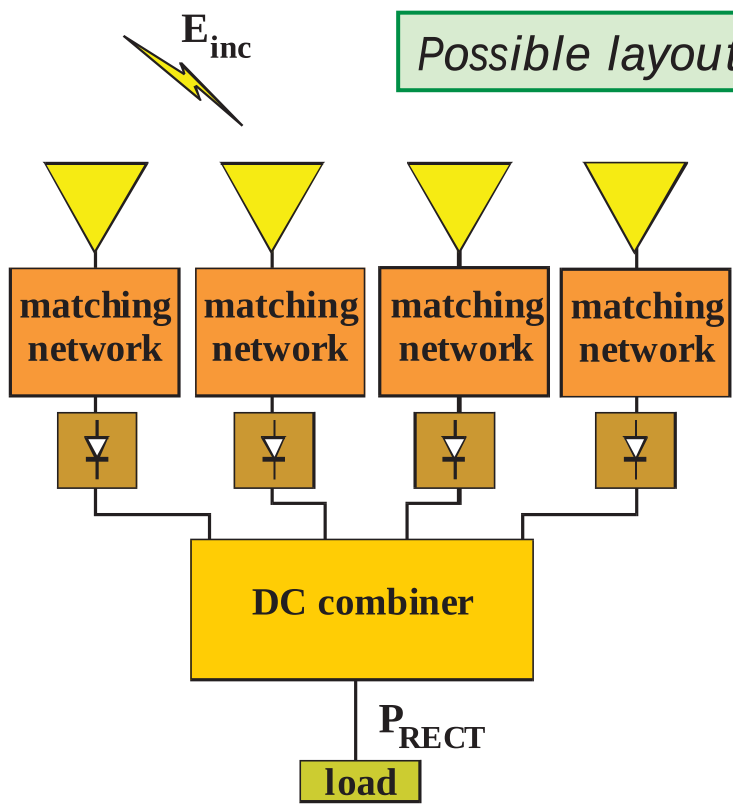
RF EH UNKNOWN info:

- Frequency source
- Source Intensity
- Polarization
- Direction of arrival

- Antennas requirements:
  - Wideband/multiband
  - Low directivity
  - Circularly polarized

Task level: *demanding*

Possible layout



Multi-element antenna & multiple rectifiers

RECTENNA FOR WPT

- Rectenna for WPT requirements:

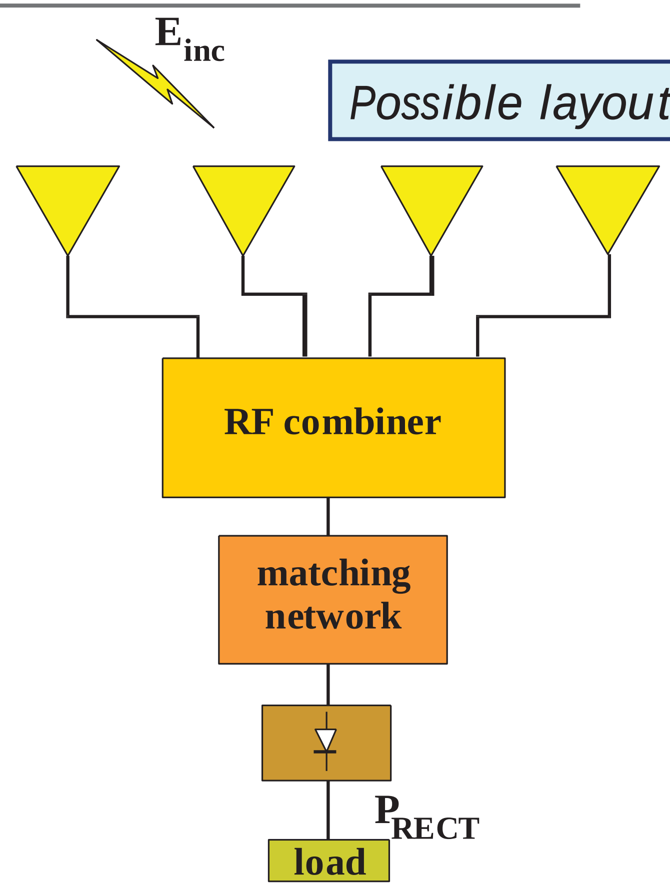
RF WPT KNOWN info:

- Frequency source
- Source Intensity
- Polarization
- Direction of arrival

Antennas requirements:

- Single frequency
- High directivity
- Linearly polarized
- Task level: medium difficulty

Possible layout

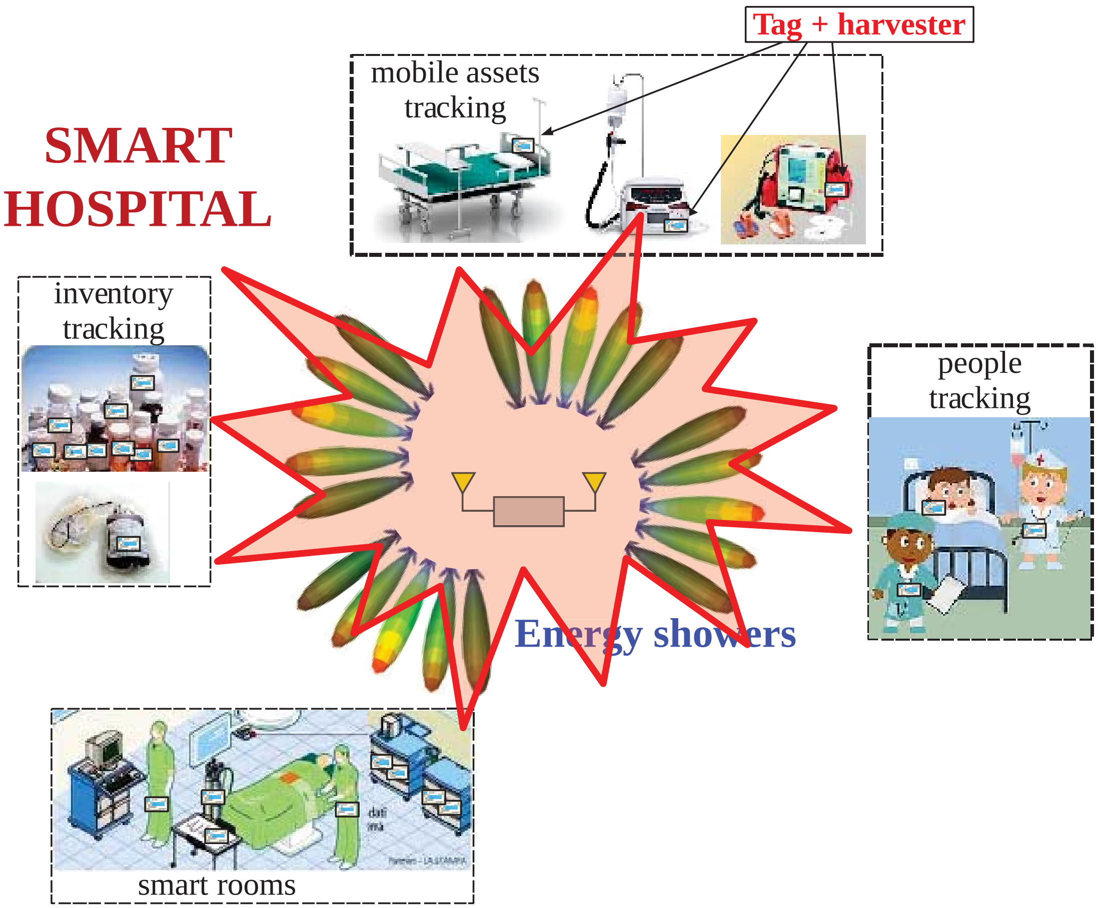


Antenna array & single rectifier

RF ENERGY TRANSMISSION

HOW TO SEND POWER?

- What about the requirements of the **RF SHOWERS**?



SOLUTIONS:

✧ ***Energy-unaware***

- almost omnidirectional behavior (highly crowded-tag scenario)
- a lot of energy is waisted

☺ ***Energy-aware***

- precise and selective powering (multi-tag scenario)

AGILE POWER TRANSMITTERS

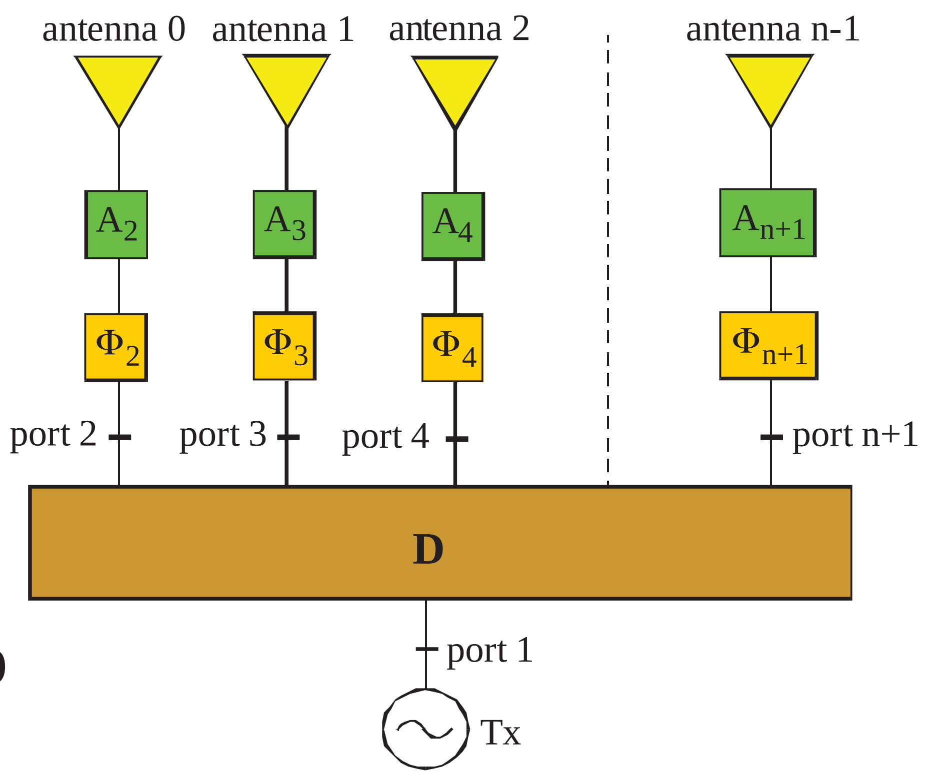
- REQUREMENTS:
  - Able to point in selected directions
  - Real-time Highly reconfigurable
  - Easy to be designed
- *complex structures*
  - PHASED ARRAYS
  - SERIES-FED/ FREQUENCY SCANNING
- *simpler solutions for IoT*
  - MONOPULSE RADAR
  - ***TIME-MODULATED ARRAYS***

PHASED ARRAYS

- *PHASED ARRAY*
  - D: n-way symmetric power divider
  - Φ_i: i-th phase shifter, electronically controlled by a voltage signal (Vi)

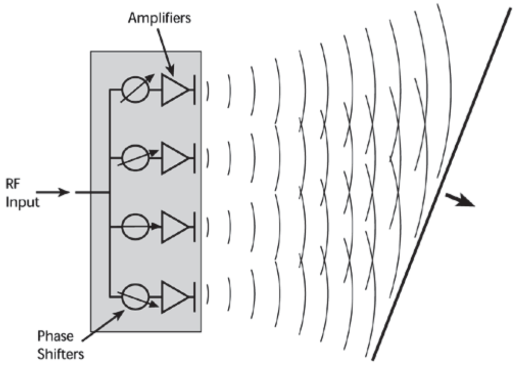
$$\Phi_{i+1}(V_{i+1}) - \Phi_i(V_i) = \delta$$
$$(2 \le m \le n)$$

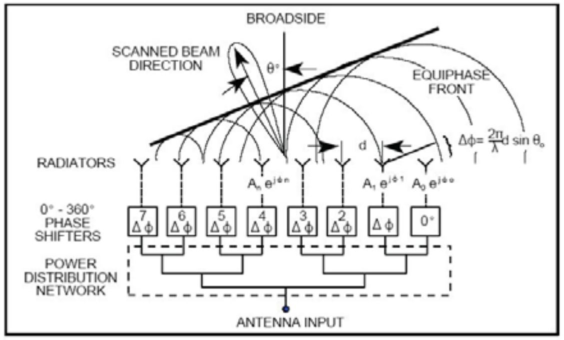
  - A_i: i-th power amplifier, to guarantee the desired powe level (or to have non-uniform arrays)



5.8 GHz LARGE PHASED ARRAY FOR MPT

5.8 GHz phased array for MPT with GaN FET and class-F amplifier, total power >1,9kW.



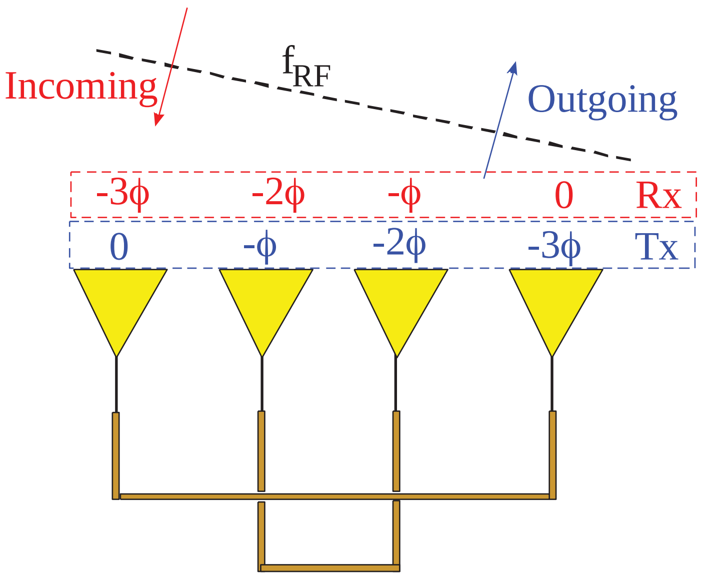


N. Shinohara, "Beam Control Technologies With a High-Efficiency Phased Array for Microwave Power Transmission in Japan," in Proceedings of the IEEE, vol. 101, no. 6, pp. 1448-1463, June 2013.

RETRODIRECTIVE ARRAY

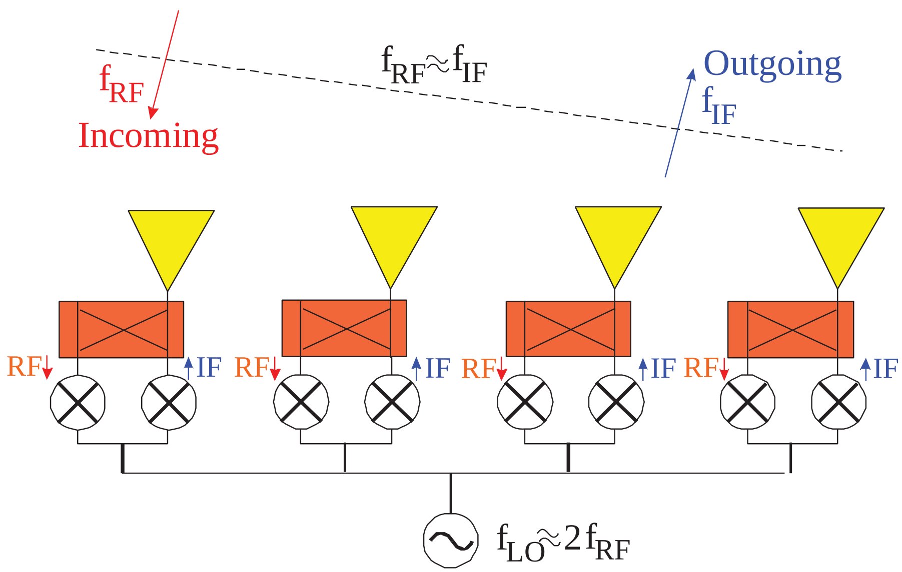
- ***RETRODIRECTIVE ARRAY:*** reflects an incident RF signal back in the direction of arrival. For applications with *relaxed* pointing accuracy and automatic beam forming

  - Van Atta RDA



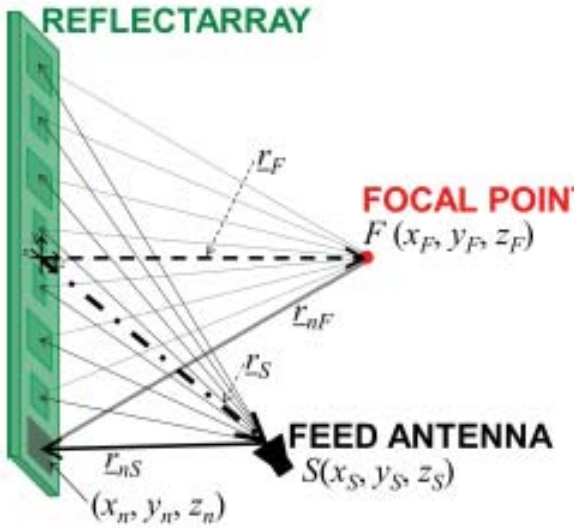
- Proper lines length provides proper phase condition

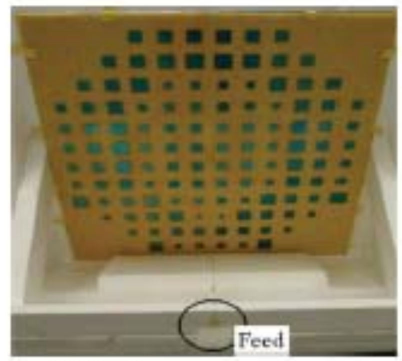
  - Pon RDA

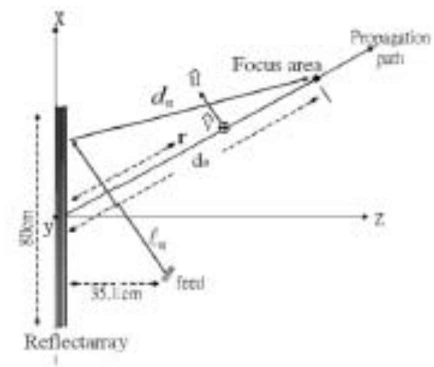


- Complex architecture (for phase-conjugation condition)

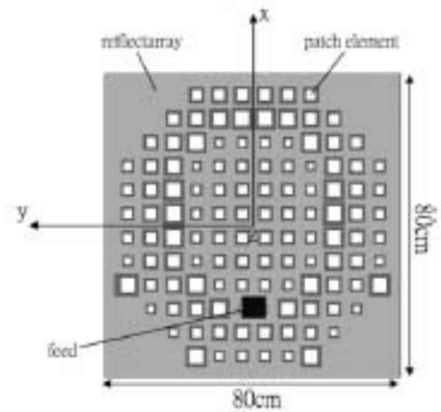
REFLECTARRAY WITH FOCAL POINTS







(a)



(b)

φ_n : phase delay to be introduced by the n-th array element

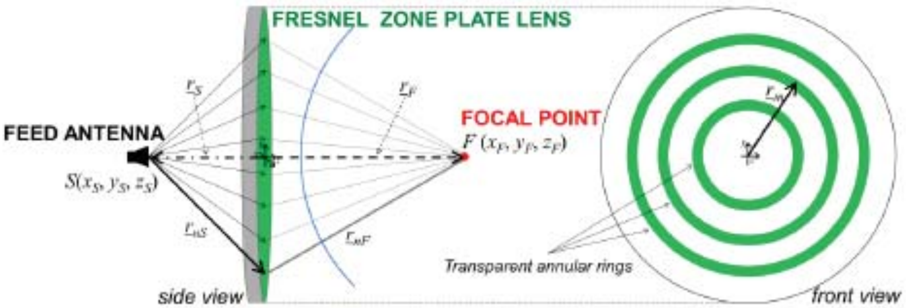
$$\varphi_n = 2\pi / \lambda \left[(r_{nS} + r_{nF}) - (r_S + r_F) \right]$$

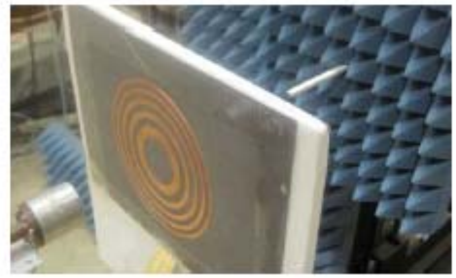
f=2.4GHz

Focal width W=7.8cm at a plane at 90cm from the reflectarray center

H.-T. Chou, T.-M. Hung, N.-N. Wang, H.-H. Chou, C. Tung, and P. Nepa, "Design of a near-field focused reflectarray antenna for 2.4 GHz RFID reader applications", *IEEE Transactions on Antennas and Propagation*, 2011

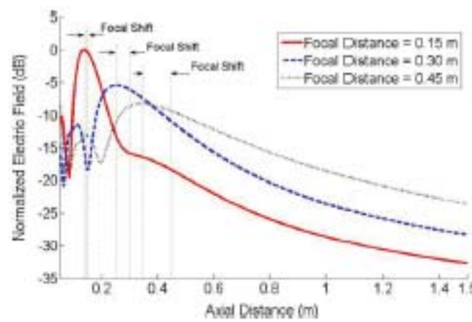
MECHANICAL TUNING OF THE FOCAL POINT

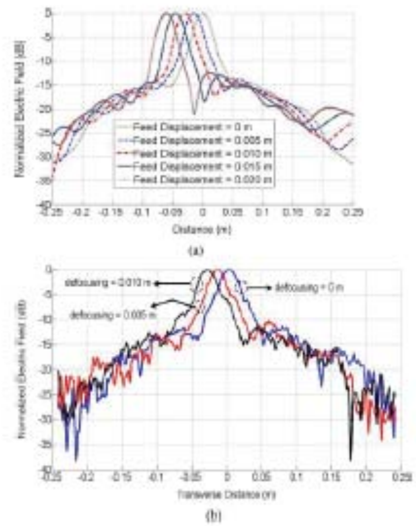




$$\left(\sqrt{r_m^2 + r_S^2} - r_S\right) + \left(\sqrt{r_m^2 + r_F^2} - r_F\right) = m\lambda / 2$$

Ka band (32GHz)
Circular plate diameter = 16cm
Feed horn at 9.5cm form the lens surface
Focus width: 1.24cm (focal length=15cm) and 3.4cm (focal length=45cm)

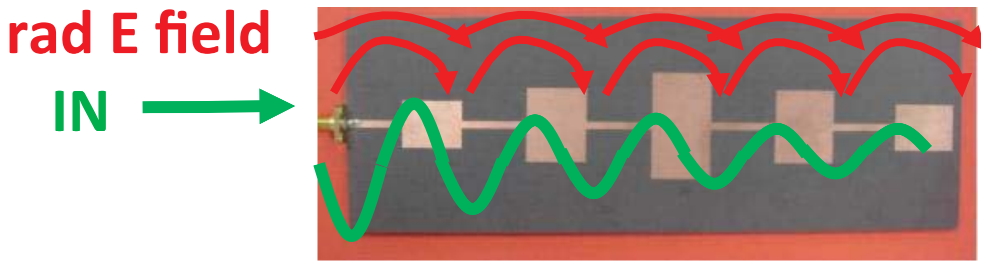


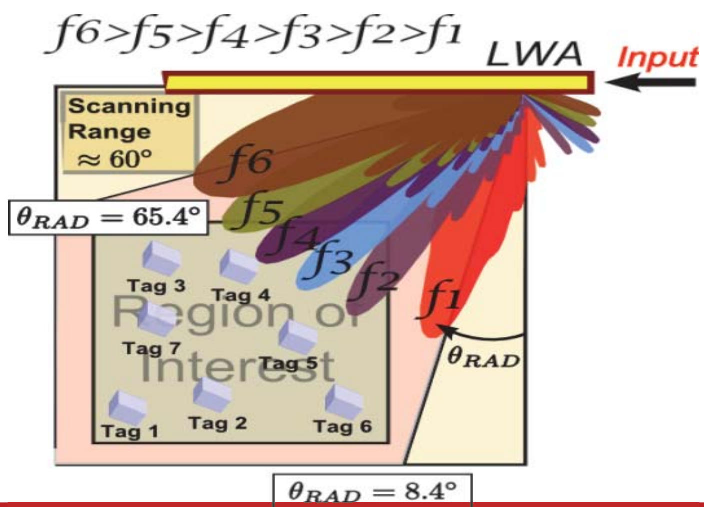


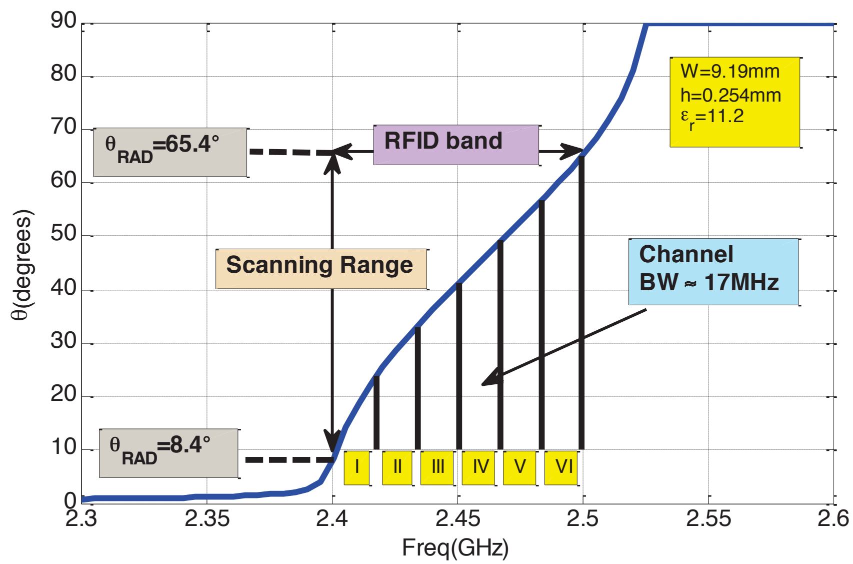
S. Karimkashi and A. A. Kishk, "Focusing Properties of Fresnel Zone Plate Lens Antennas in the Near-Field Region,"

SERIES-FED ARRAY FOR FREQUENCY SCANNING

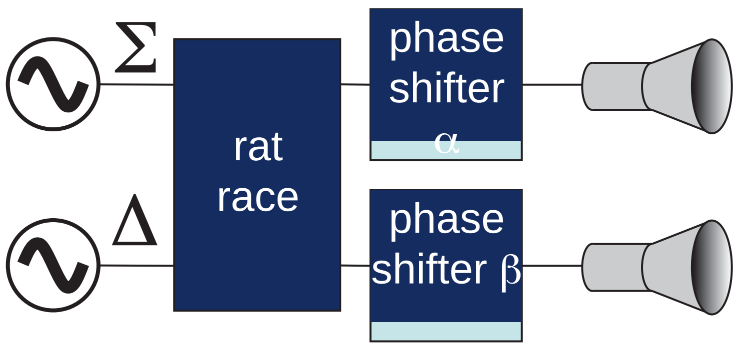
- Resonant periodic strips / slots fed by a travelling wave instead of a discrete distributed network:
  - Fixed beam for a fixed frequency
  - (Limited) steering capability in a frequency band

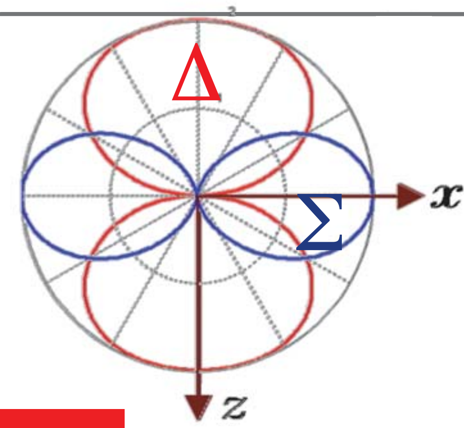






READER ANTENNA SYSTEM: MONOPULSE RADAR





Σ array factor

$$F_{\Sigma}(\vartheta,\varphi) = e^{j\left(\frac{\pi L}{\lambda}\cos\vartheta - \alpha\right)} + e^{-j\left(\frac{\pi L}{\lambda}\cos\vartheta + \beta\right)}$$

Δ array factor

$$F_{\Delta}(\vartheta,\varphi) = e^{j\left(\frac{\pi L}{\lambda}\cos\vartheta - \alpha\right)} - e^{-j\left(\frac{\pi L}{\lambda}\cos\vartheta + \beta\right)}$$

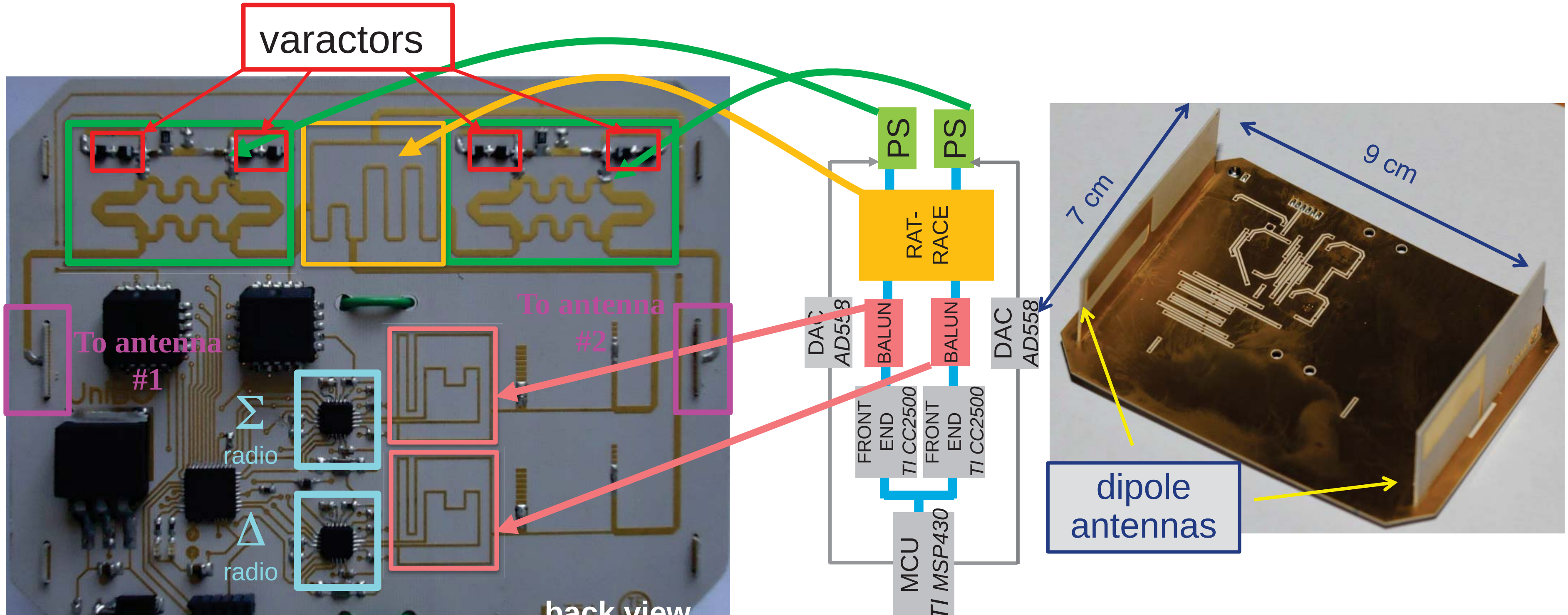
two-element array: *monopole antenna* (almost omnidirectional)

⇒ the array radiation pattern is shaped by in-phase (Σ) and out-of-phase (Δ) array factors only:

⇒ same shape in any pointing direction

Σ and Δ directions are varied by simultaneously controlling two phase-shifters

READER WITH DETECT AND SELECT CAPABILITIES



M. Del Prete, D. Masotti, N. Arbizzani, and A. Costanzo, "Remotely Identify and Detect by a Compact Reader With Mono-Pulse Scanning Capabilities", *IEEE Transactions on Microwave Theory and Techniques,* Vol. 61, No. 1, Part II, Jan. 2013, pp. 641-650

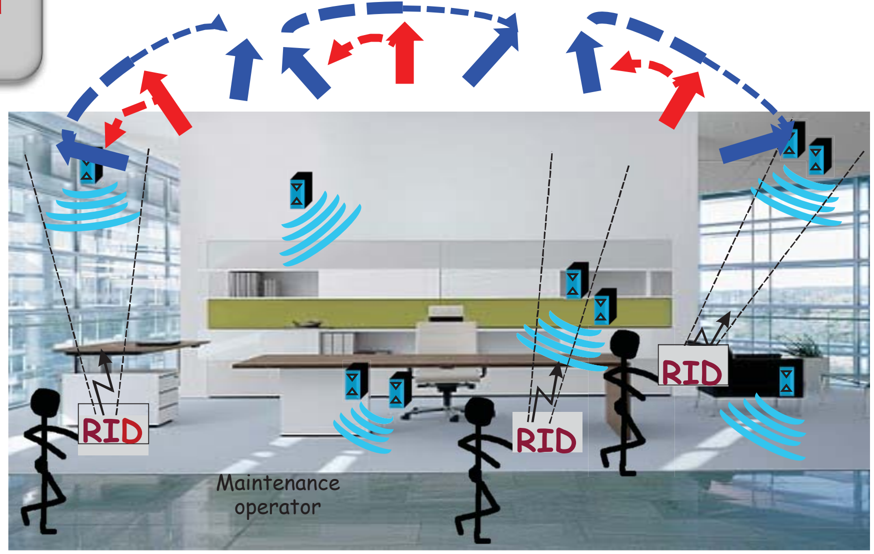
- Challanges:
  - Layout-wise design of phase-shifters
  - Nonlinear relationship between varactors bias and phase-shift

OBJECTS DETECTION

RID

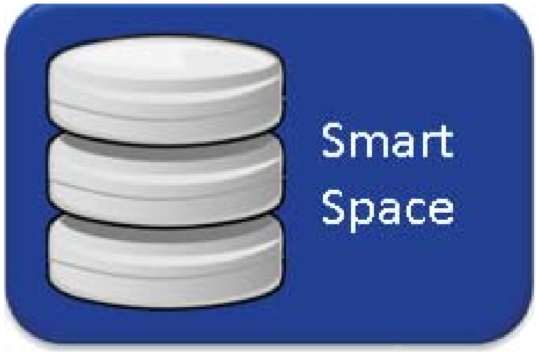
starts searching for the object with the ID acquired during "selection

COARSE POSITIONING
activate closely-spaced Tags
measure of RSSI at the Σ RID ports

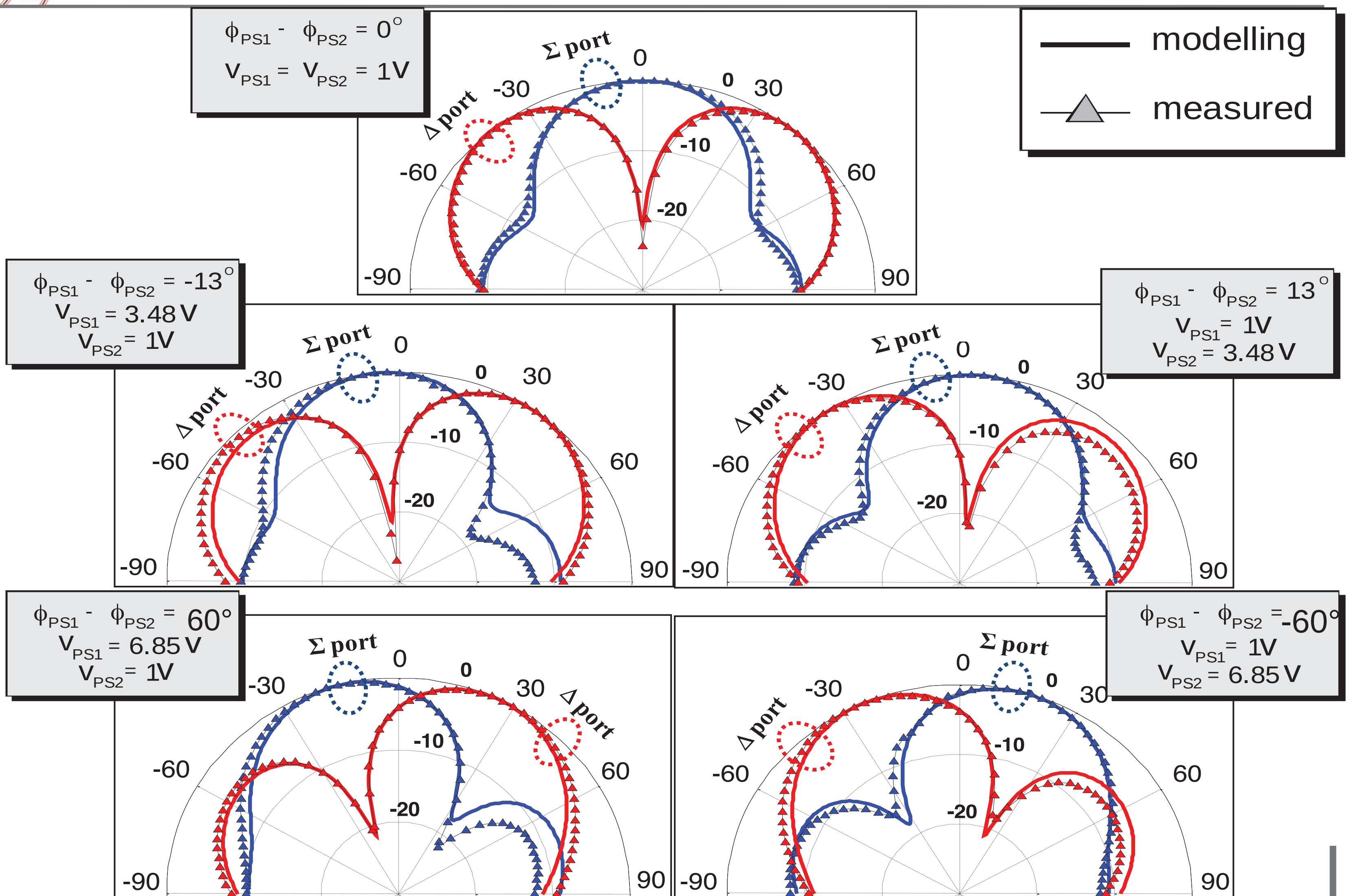


FINE POSITIONING
monopulse RADAR measure of RSSI at the Σ and Δ READER ports of tags placed around pointed position (same as in selection mode)

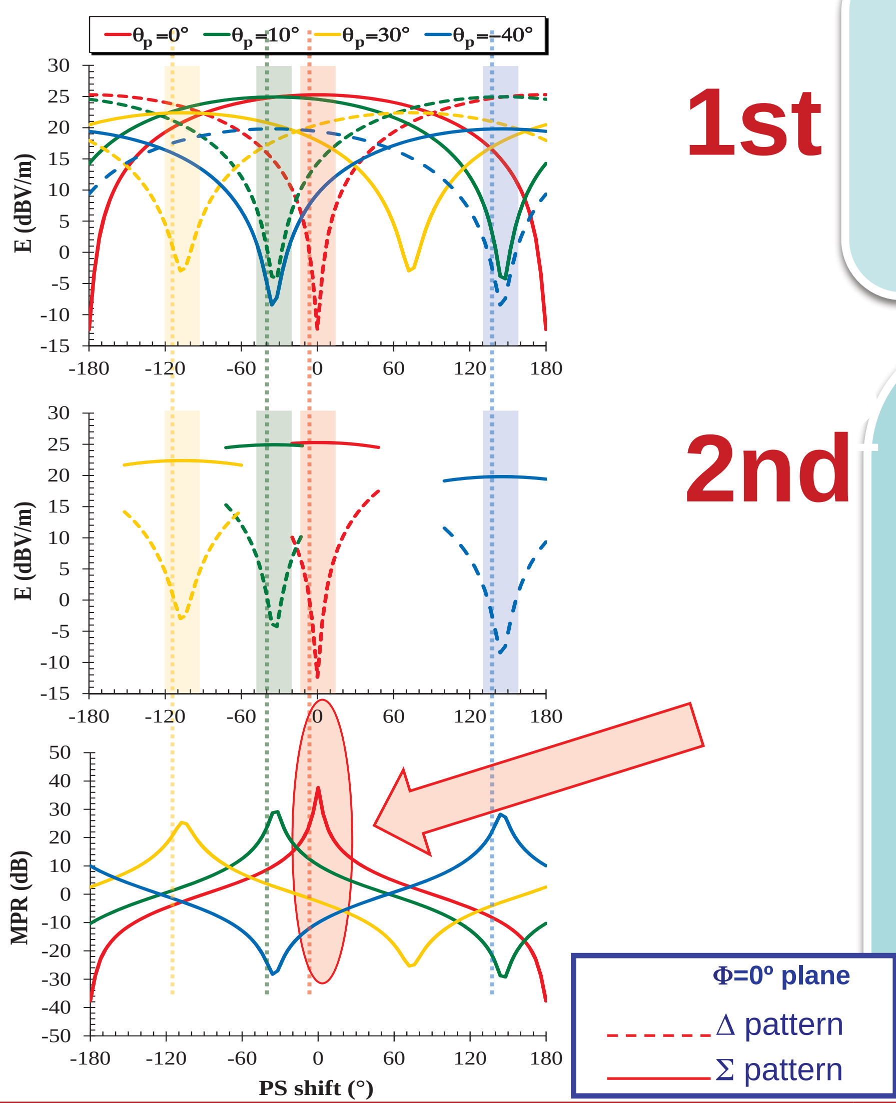
performs action and update object properties/state



COMPUTED AND MEASURED Σ AND Δ PERFORMANCE



OBJECT SELECTION IN 2 STEPS



1st

IDs ACQUISITION

(*only the Σ radio is involved*):

- RID points to the desired object
- Inquire for IDs

2nd

SCANNING OPERATION

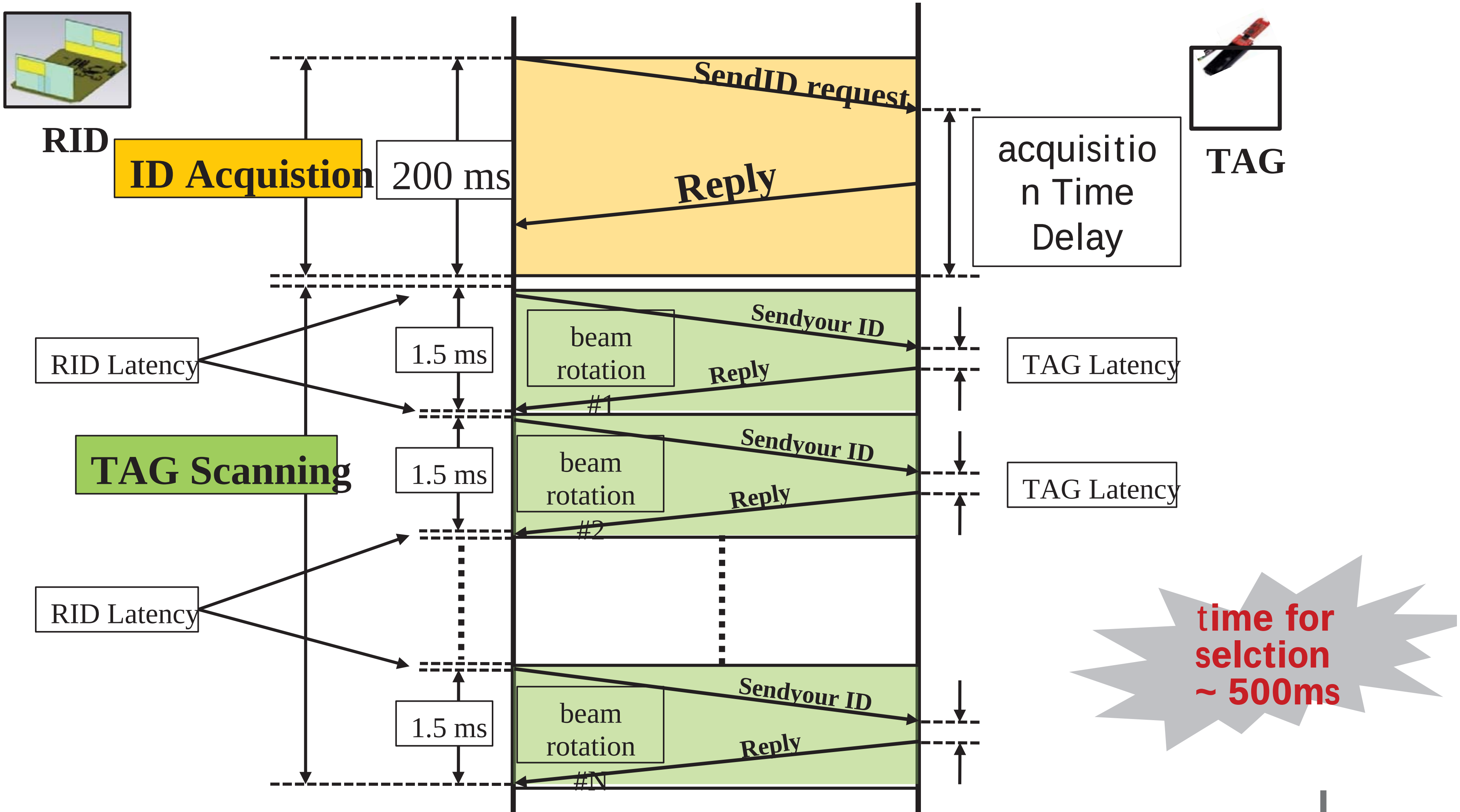
Σ and Δ radios ***cooperate*** exploiting the scanning capabilities of the RID

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

$$MPR = \Sigma_{RSSI}[dB] - \Delta_{RSSI}[dB]$$

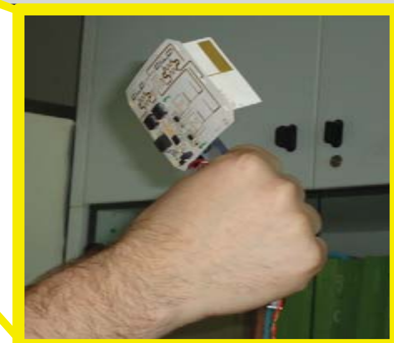
The BEST CENTERED MPR is the POINTED OBJECT (scanning zone (θ= ±45°) swept in 40 steps, 1.5 ms each)

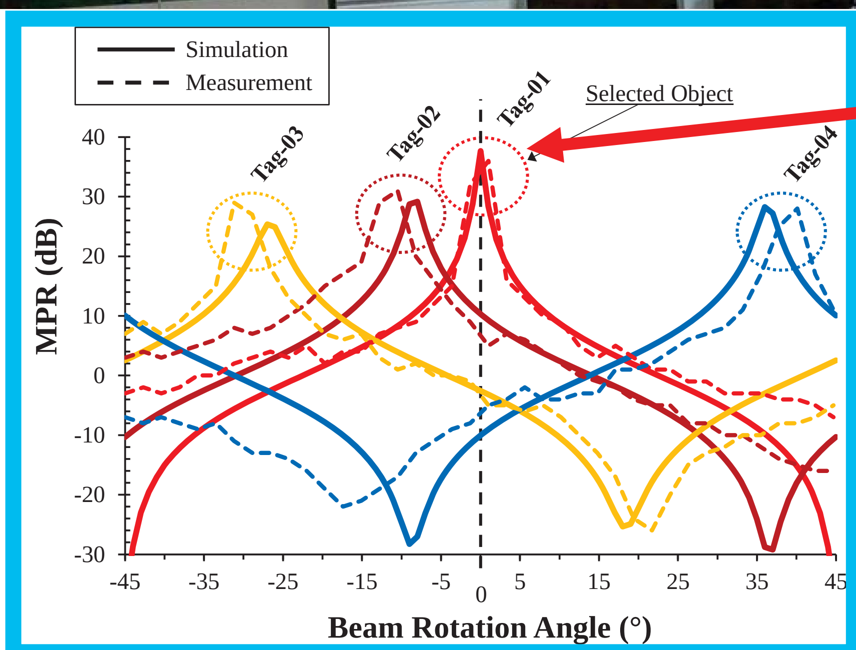
ACTIVITY DIAGRAM



OBJECT SELECTION IN HARSH EM ENVIRONMENTS

GOAL
select Tag-01, Tag-03
READING zone
beam steering:±45
⇒±180°phase-shifts outputs





tag-01 shows the best mpr at a 0-rotation angle

PREDICTED AND MEASURED MPR:
RID POINTING TO CENTRAL TAG

excellent agreement with prediction

(*carried out in free-space conditions*)

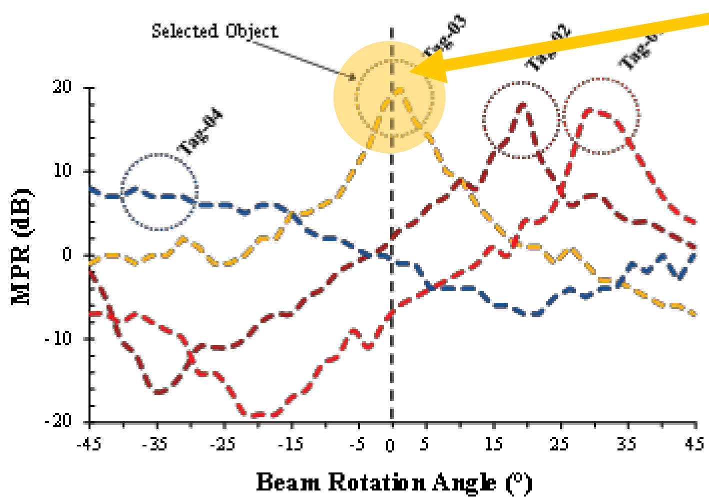
NOTE: environment under test with severe multipath scenario

MEASURED PERFORMANCE OF RID FOR SELECTION OF TAG-03

RID POINTS TO TAG-03:

- the S and D radiation patterns rotate symmetrically around the RID pointing position.

SELECTION SUCCEDED! the best centered absolute maximum of MPR, corresponds to Tag-03.



Tag-03 SHOWS THE BEST MPR AT A 0°ROTATION ANGLE

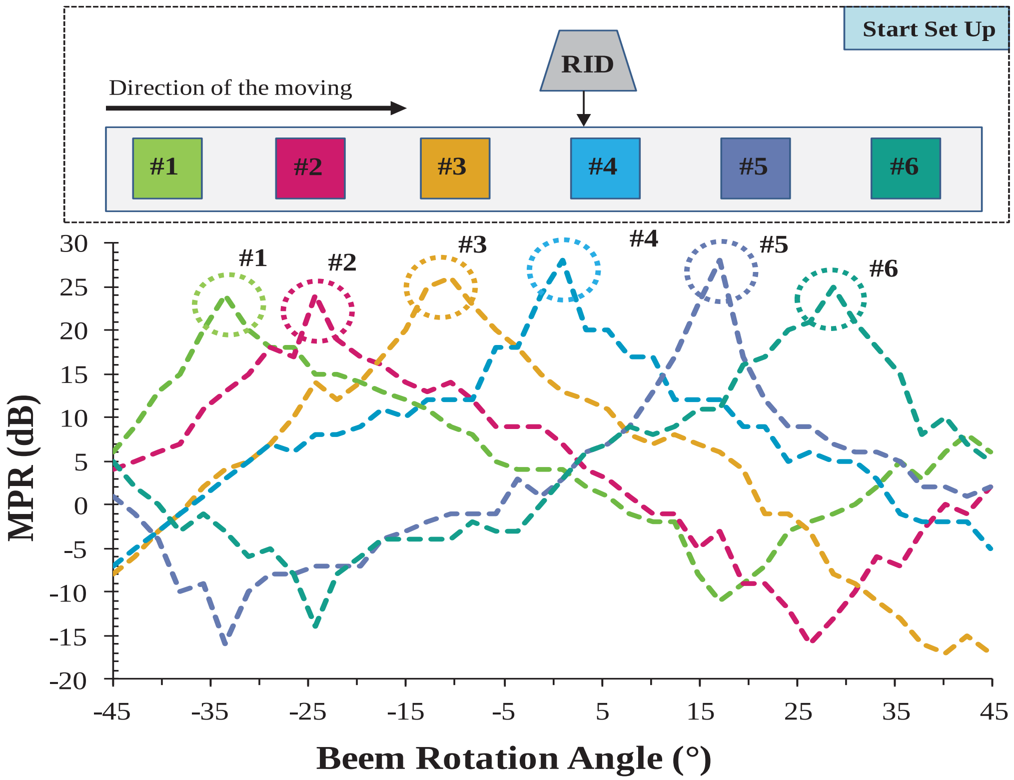
OBJECTS LOCALIZATION

By ***beam steering*** RID also acquires others tags relative locations

INFACT allowed rotation angles are well within the allowed performance of the phase shifter outputs.

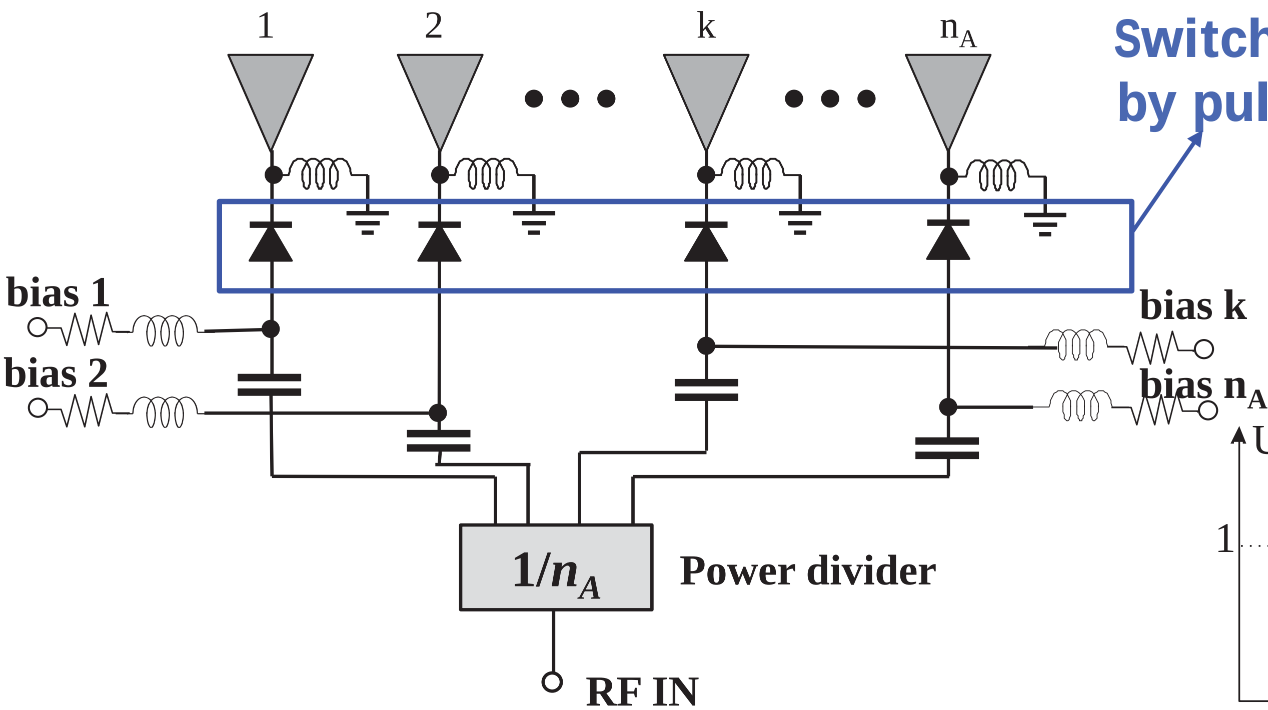
SET UP TO RECORDING THE SEQUENCE OF MOVING OBJECTS

RID is positioned perpendicular to the objects plane
Recognizes the sequence correctly.
This operation requires less than 500 ms



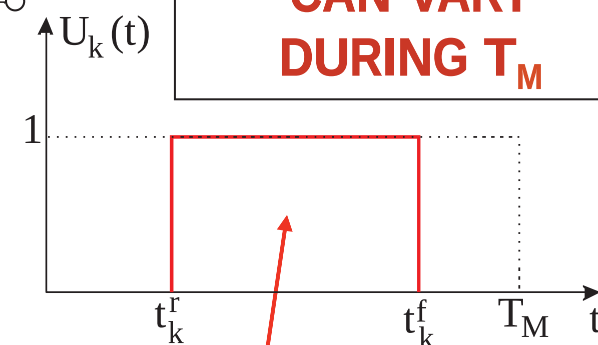
Time-modulated arrays (TMAs)

TIME MODULATED ARRAY ARCHITECTURE



Switches controlled by pulse sequences

EACH ANTENNA EXCITATION AMPLITUDE CAN VARY DURING T_M



ARRAY FACTOR OF A STANDARD LINEAR ARRAY

$$AF(\theta,\phi) = \sum_{k=0}^{n_A-1} \Lambda_k \, e^{j\delta_k} \, e^{jk\beta L \sin\theta}$$

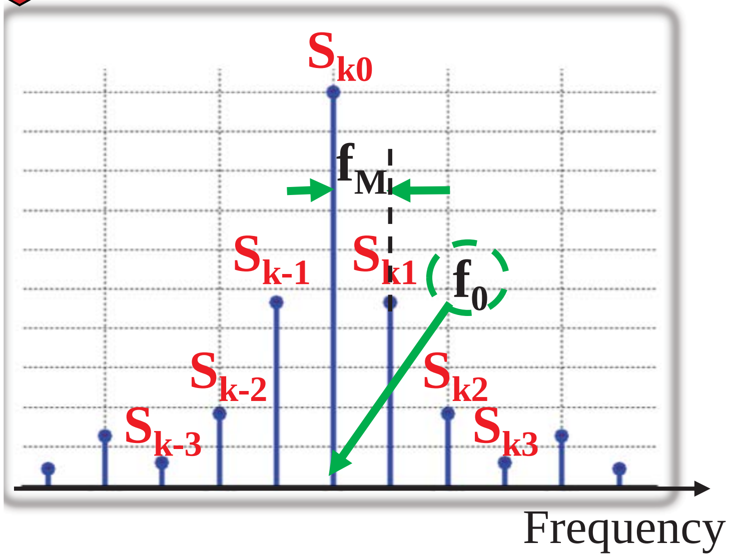
ARRAY FACTOR OF A LINEAR TMA

$$AF(\theta,\phi,t) = \sum_{k=0}^{n_A-1} \Lambda_k U_k(t) e^{j\delta_k} \, e^{jk\beta L \sin\theta}$$

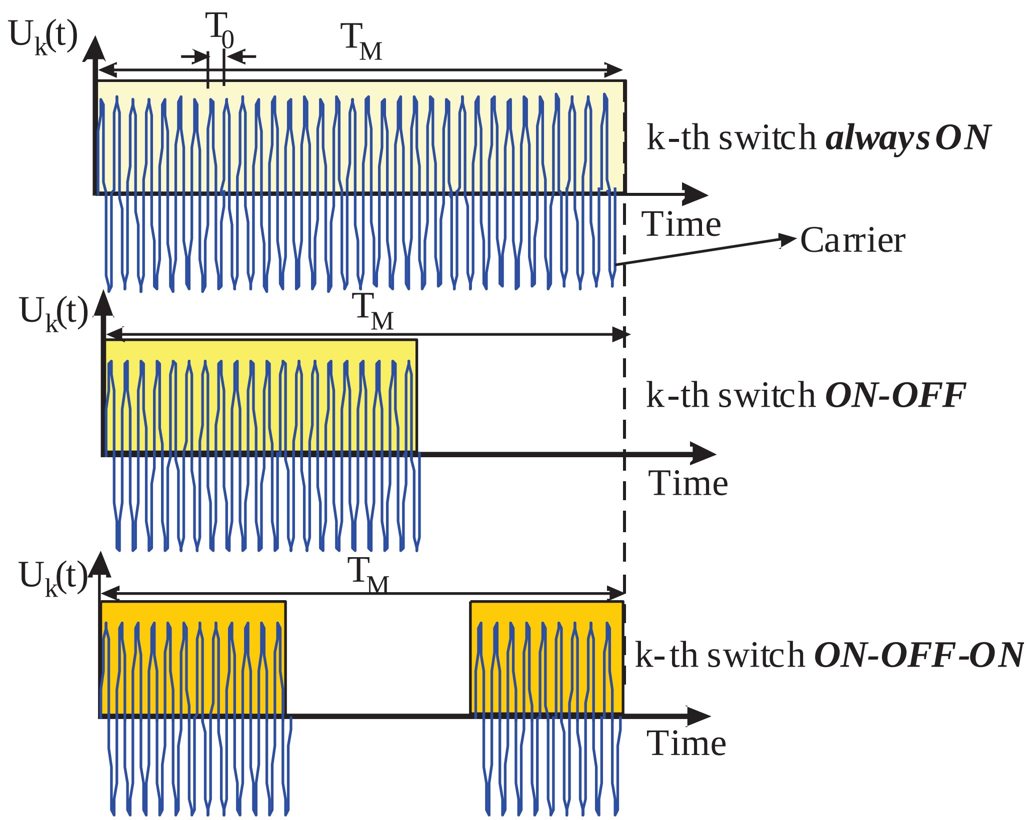
TIME MODULATED ARRAY EXCITATION SPECTRA

- T_M, f_M : period and frequency of switch modulation
- T_0, f_0: period and frequency of ***sinusoidal*** RF carrier

$T_M = 1/f_M >> T_0 = 1/f_0$



Control pulses

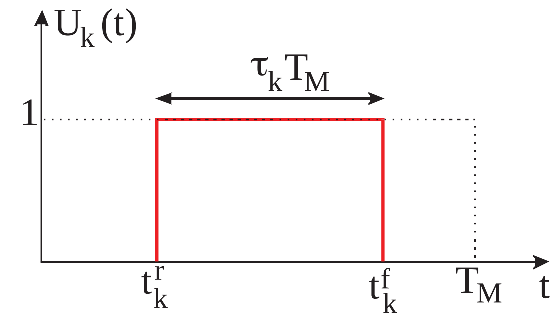


TIME-DEPENDENT ARRAY FACTOR

$$AF(\theta,\phi,t) = \sum_{h=-\infty}^{\infty} AF_h(\theta,\phi,t) =$$

$$= \sum_{h=-\infty}^{\infty} e^{j2\pi(f_0 + hf_M)t} \sum_{k=0}^{n-1} \Lambda_k u_{hk} e^{jk\beta L\cos\psi}$$

$\Lambda_k \rightarrow 1$



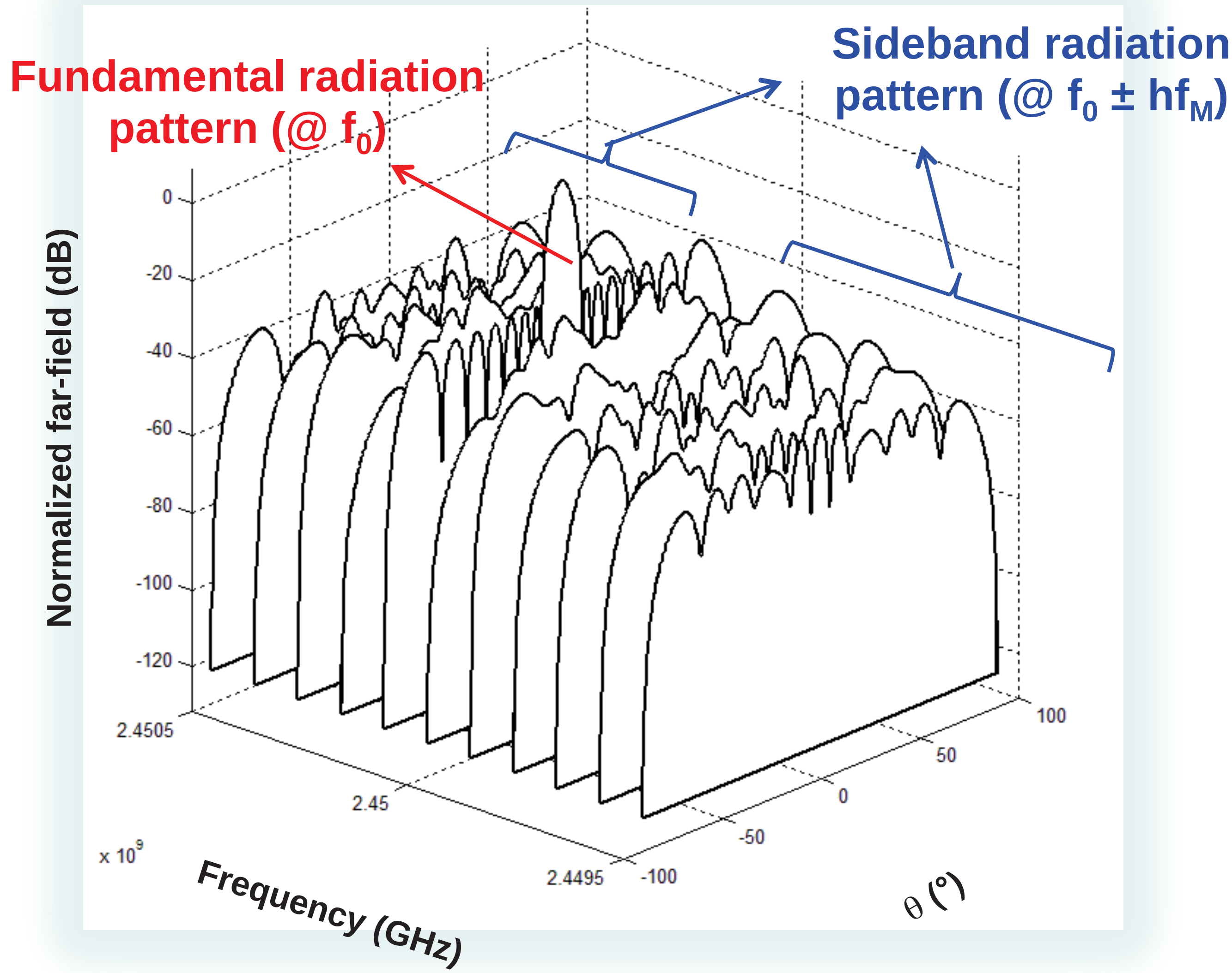
$\tau_K T_M$= k- switch duration of the ON state

Fourier coefficients of $U_k(t)$:

$$u_{hk} = \frac{1}{T_M}\left(\frac{e^{-jh\omega_M t_k^r} - e^{-jh\omega_M t_k^r - \tau_k T_M}}{jh\omega_M}\right) \; ; \; u_{0k} = \tau_k \text{ (real)}$$

- Due to switch modulation the array is able to radiate:
  - at the *fundamental carrier (h=0)*
  - at the *sideband harmonics (h≠0)*

TMA RADIATION @ FUNDAMENTAL AND SIDE BANDS



TMA POTENTIALS

- ***Time*** as an array further design parameter:

- almost unlimited **control sequence combinations** in TMAs
- ease implementation fast switching control

ANTENNA RECONFIGURATION IN REAL TIME!

NO NEED FOR:

1. phase shifters and complex feeding networks (*as phased arrays*)
2. Large array structure (*as leaky wave antennas*)
3. Large array structure with broadband matching constraints (*as frequency scanning antenna)*
4. Mechanical tuning of the focal point

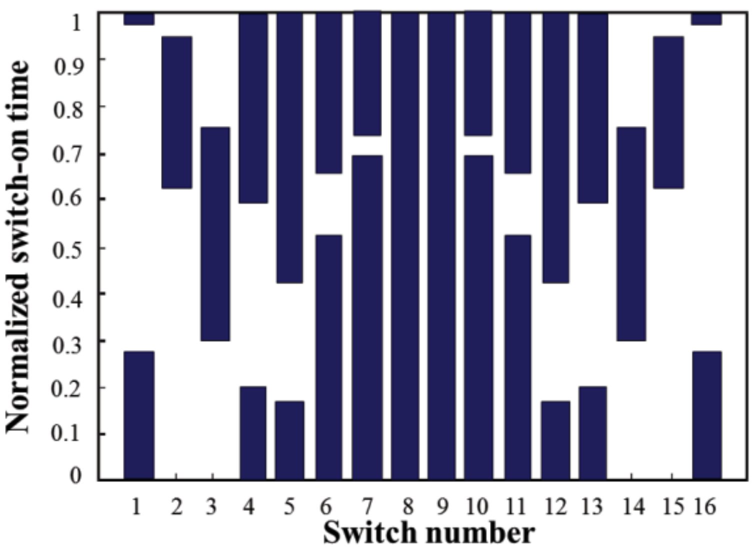
- Make TMA a versatile and adequate radiation system for modern wireless applications (e.g. SDR)

TMAs CONTROL SEQUENCE EXAMPLES: 1- SIDE LOBES REDUCTION

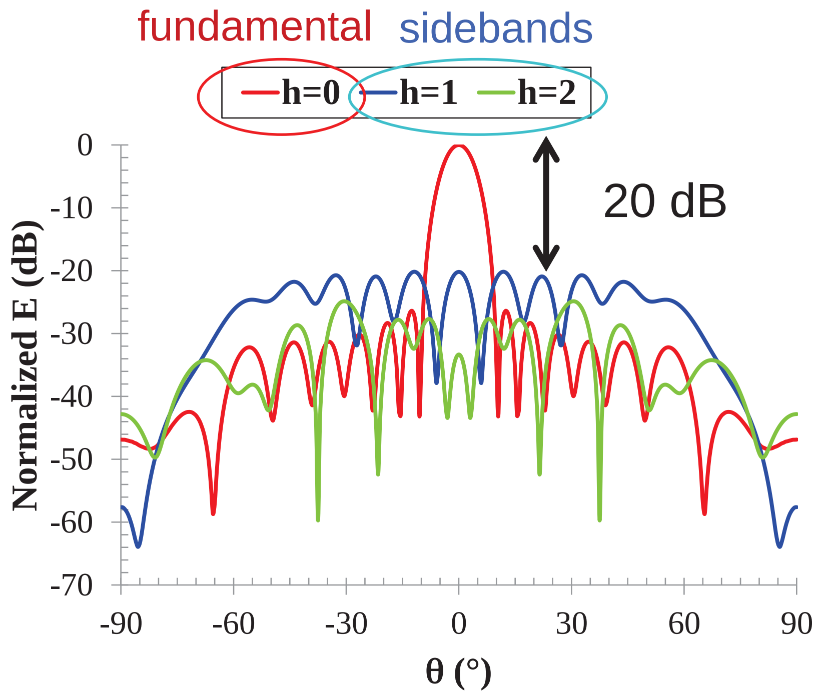
- ***16-element array***

Switch ON time

Switch OFF time



Theoretical radiation pattern



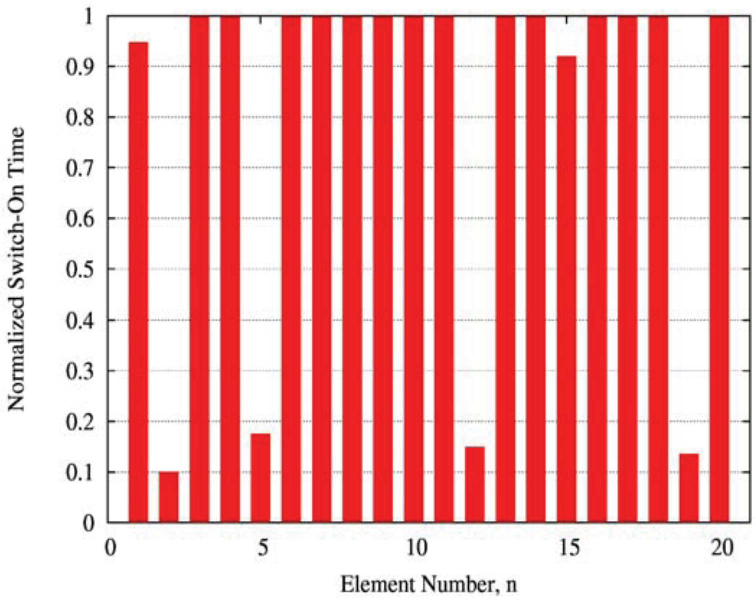
L. Poli, P. Rocca, L. Manica, A. Massa, “Pattern synthesis in time-modulated linear arrays through pulse shifting," *IET Microwaves, Ant. & Prop.*, vol. 4, no. 9, pp. 1157-1164, Sept. 2010

TMAs CONTROL SEQUENCE EXAMPLES: 2- HARMONIC NULLING

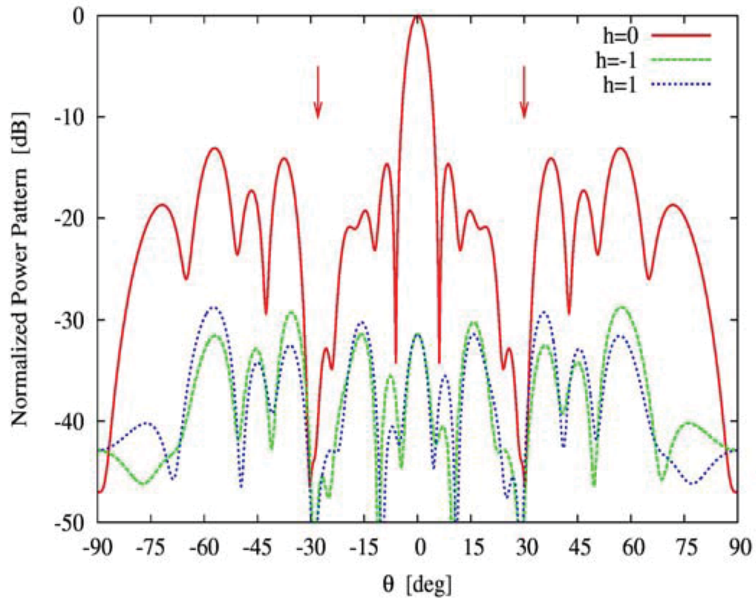
20-element array

Switch ON time

Switch OFF time



Theoretical radiation pattern

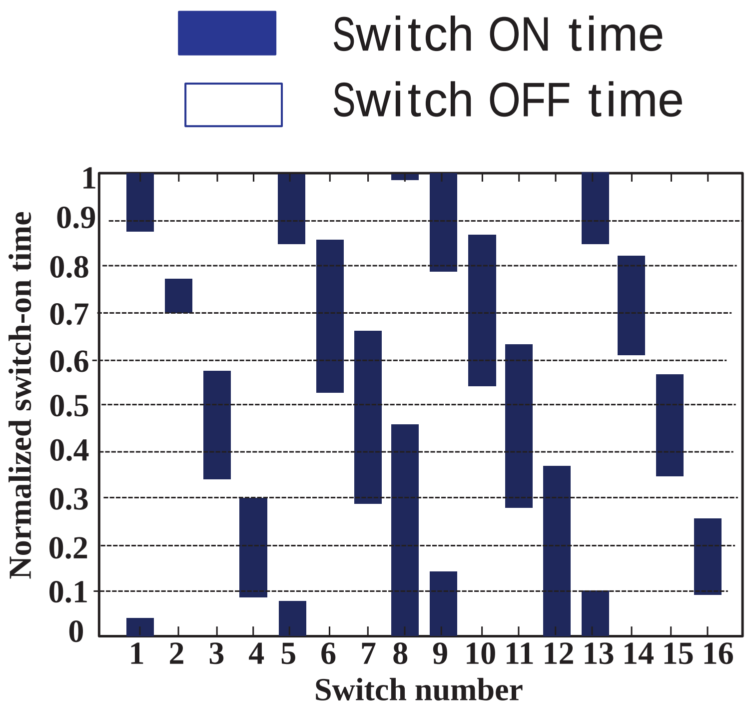


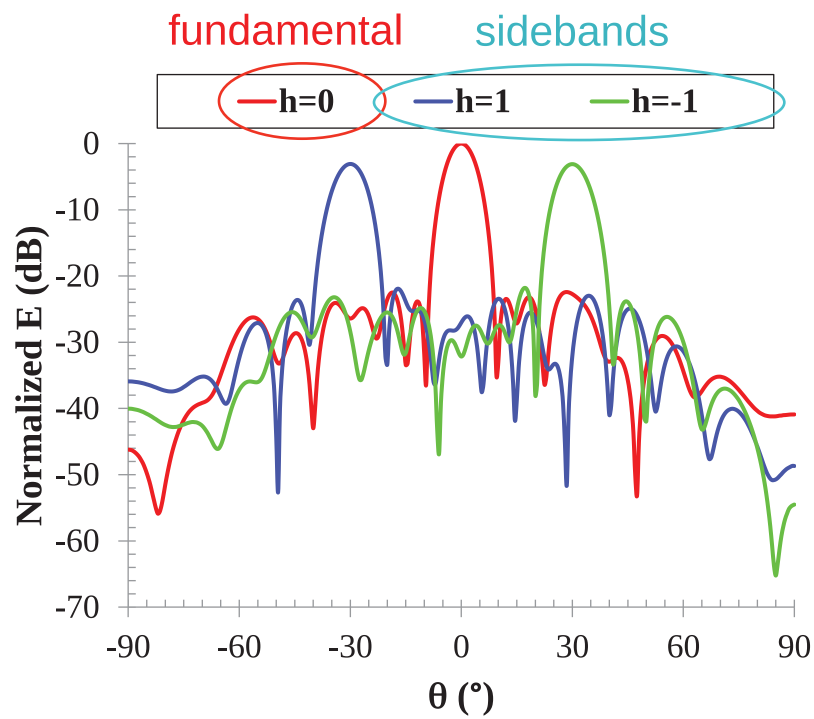
L. Poli, P. Rocca, G. Oliveri, and A. Massa, "Adaptive nulling in time-modulated linear arrays with minimum power losses," *IET Microwaves, Antennas & Propagation*, vol. 5, no. 2, pp. 157-166, 2011

TMAs CONTROL SEQUENCE EXAMPLES: 2- HARMONIC BEAMFORMING

- Exploitation of multi-channel features ***harmonic beamforming***.

predicted radiation pattern



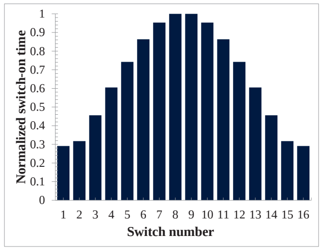


L. Poli, P. Rocca, G. Oliveri, A. Massa, "Harmonic beamforming in time-modulated linear arrays through particle swarm optimization", *IEEE Trans. Ant. & Prop.*, vol. 59, no. 7, pp. 2538-2545, July 2011

TMA analysis/design

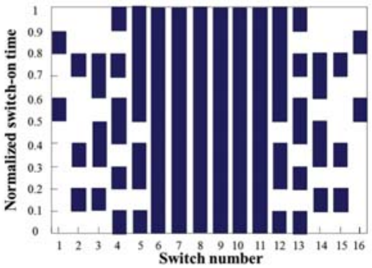
TMAs SEQUENCE OPTIMIZATION

Available TMA design methods focus on control sequence optimization, but rely on *ideal* radiating elements and *ideal control switches*



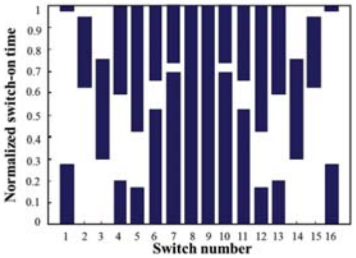
VARIABLE APERTURE SIZE:

design parameter: pulse length



BINARY OPTIMIZED TIME SEQUENCE

design parameter: pulse sub-intervals



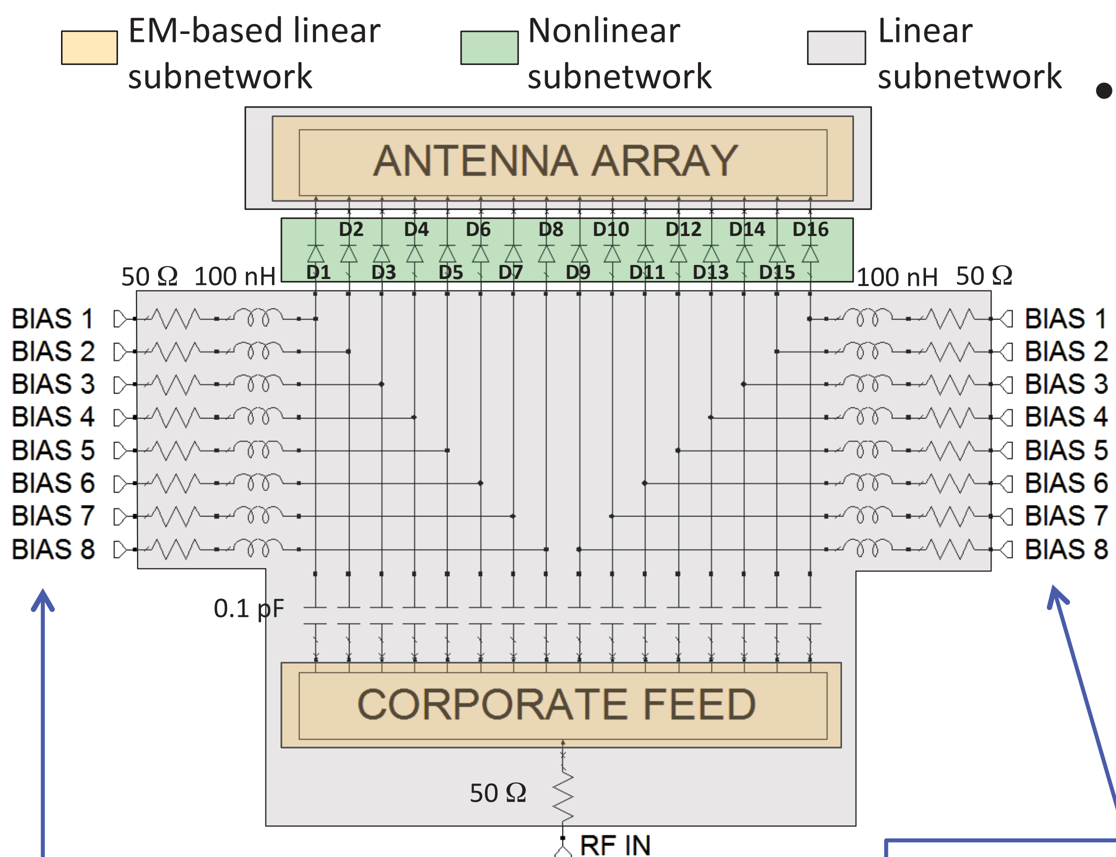
PULSE SHIFTING

design parameter: pulse switch on time interval

W. H. Kummer, A. T. Villeneuve, T. S. Fong, and F. G. Terrio, "Ultra-low sidelobes from time-modulated arrays," *IEEE Trans. on Ant. and Prop.*, vol.AP-11, no. 6, pp. 633-639, Nov. 1963

NL/EM TMAs CO-SIMULATION

Piecewise Harmonic-Balance method



- a ***nonlinear*** subnetwork, consisting of the diodes

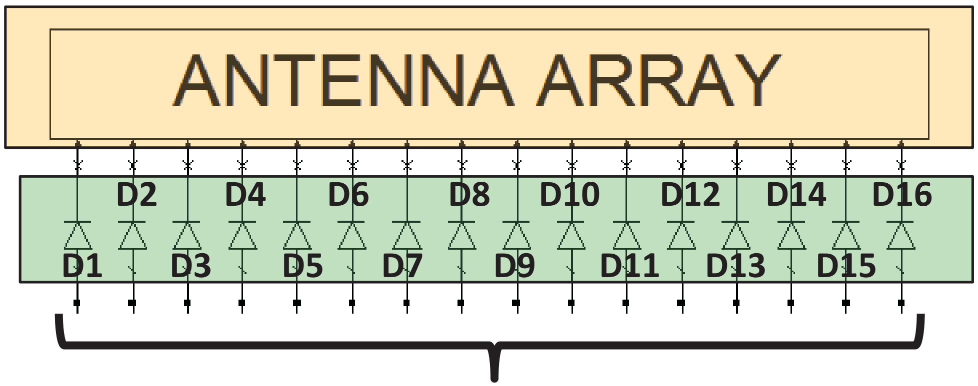
  a ***linear*** subnetwork, including
  - the EM-based part (array and feeding network)
  - the lumped components

Rizzoli, D. Masotti, F. Mastri, E. Montanari, "System-Oriented Harmonic-Balance Algorithms for Circuit-Level Simulation", *IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems*, Feb. 2011, vol. 30, no. 2, pp. 256 – 269

NL/EM TMAs CO-SIMULATION

EVALUATION OF THE TMA RADIATION PERFORMANCE

Under sinusoidal regime



Antenna linearity

spectrum harmonics

$$\mathbf{i}_A^{(i)}(t) = \mathrm{Re}\left[\sum_{k=1}^{n_H} \mathbf{I}_{A,k}^{(i)} \exp(jk\omega_0 t)\right]$$

Current at i-th diode port

Field at the fundamental harmonic

$$\mathbf{E}(r,\theta,\phi;\omega_0) = \frac{\exp(-j\beta r)}{r} \bullet \sum_{i=1}^{n_A}\left[\hat{\theta}\, A_\theta^{(i)}(\theta,\phi;\omega_0) + \hat{\phi}\, A_\phi^{(i)}(\theta,\phi;\omega_0)\right] I_{A,1}^{(i)}$$

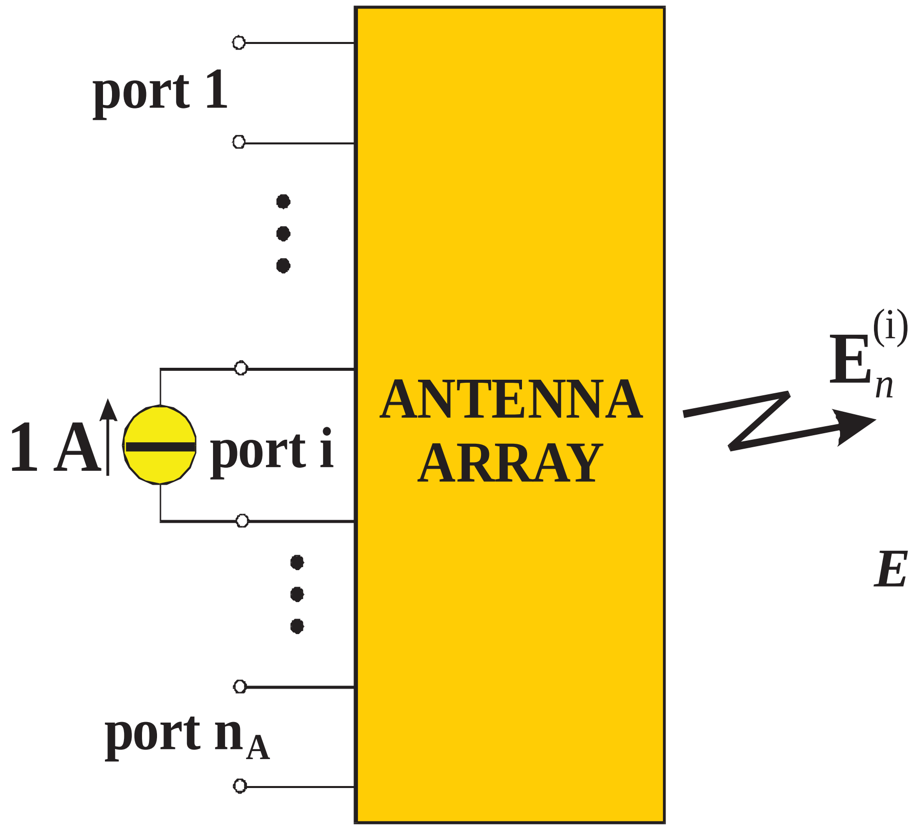
Array ports

$$A_\theta^{(i)},\ A_\phi^{(i)}$$

are the scalar components of the normalized field generated by EM simulation

V. Rizzoli, A. Costanzo, and D. Masotti, "Coupled nonlinear/electromagnetic CAD of injection-locked self-oscillating microstrip antennas", *Int. Journal RF and Microwave Computer-Aided Eng.*, vol. 13, Sept. 2003, pp. 398-414

Field evaluation



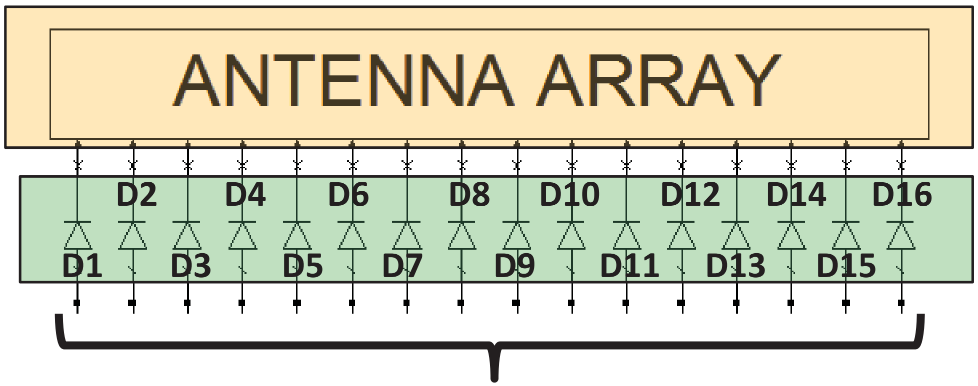
given the i-th antenna array port, the corresponding radiated field is:

$$\boldsymbol{E}_n^{(i)}(r,\theta,\phi,\omega_0) =$$
$$\hat{\boldsymbol{\theta}}\,\mathrm{E}_{n\theta}^{(i)}(r,\theta,\phi,\omega_0) + \hat{\boldsymbol{\varphi}}\,\mathrm{E}_{n\phi}^{(i)}(r,\theta,\phi,\omega_0) =$$
$$\frac{\mathrm{e}^{-\mathrm{j}\beta r}}{r}\left[\hat{\boldsymbol{\theta}}\,\mathrm{A}_{\theta}^{(i)}(\theta,\phi,\omega_0) + \hat{\boldsymbol{\varphi}}\,\mathrm{A}_{\phi}^{(i)}(\theta,\phi,\omega_0)\right]$$

NL/EM TMAs CO-SIMULATION

Under modultaed regime ON/OFF switching

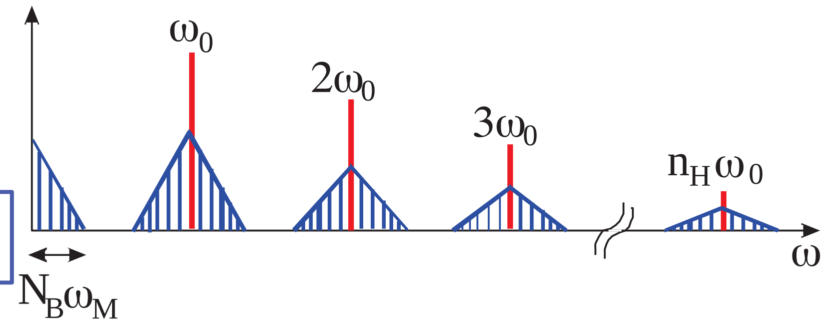
Far-field evaluation: **modulated regime**



fast carrier time | slow modulation time

$T_M=2\pi/\omega_M >> T_0=2\pi/\omega_0$

circuit-envelope HB



$$\mathbf{i}_A^{(i)}(t,t_M) = \mathrm{Re}\left[\sum_{k=1}^{n_H} \mathbf{I}_{A,k}^{(i)}(t_M)\exp(jk\omega_0 t)\right]$$

Generic excitation current *(at i-th port)*

$$\mathbf{I}_{A,k}^{(i)}(t_M) = \sum_{h=-N_B}^{N_B} \mathbf{I}_{A,kh}^{(i)}\exp(jh\omega_M t_M)$$

time-dependent complex k-th envelope (or modulation law)

NL/EM TMAs FAR-FIELD PREDICTION

Under modulated regime ON/OFF switching

$$\mathbf{E}_1(r,\theta,\phi;t_M) = \frac{\exp(-j\beta r)}{r} \bullet$$

$$\bullet \sum_{i=1}^{n_A}\left[\hat{\boldsymbol{\theta}}\, A_\theta^{(i)}(\theta,\phi;\omega_0) + \hat{\boldsymbol{\phi}}\, A_\phi^{(i)}(\theta,\phi;\omega_0)\right] I_{A,1}^{(i)}(t_M) -$$

$$- j\,\frac{1}{r}\left[\sum_{i=1}^{n_A} \left.\frac{\partial\left\{\exp(-j\beta r)\left[\hat{\boldsymbol{\theta}}\, A_\theta^{(i)}(\theta,\phi;\omega) + \hat{\boldsymbol{\phi}}\, A_\phi^{(i)}(\theta,\phi;\omega)\right]\right\}}{\partial\omega}\right|_{\omega=\omega_0} \bullet \frac{dI_{A,1}^{(i)}(t_M)}{dt_M}\right]$$

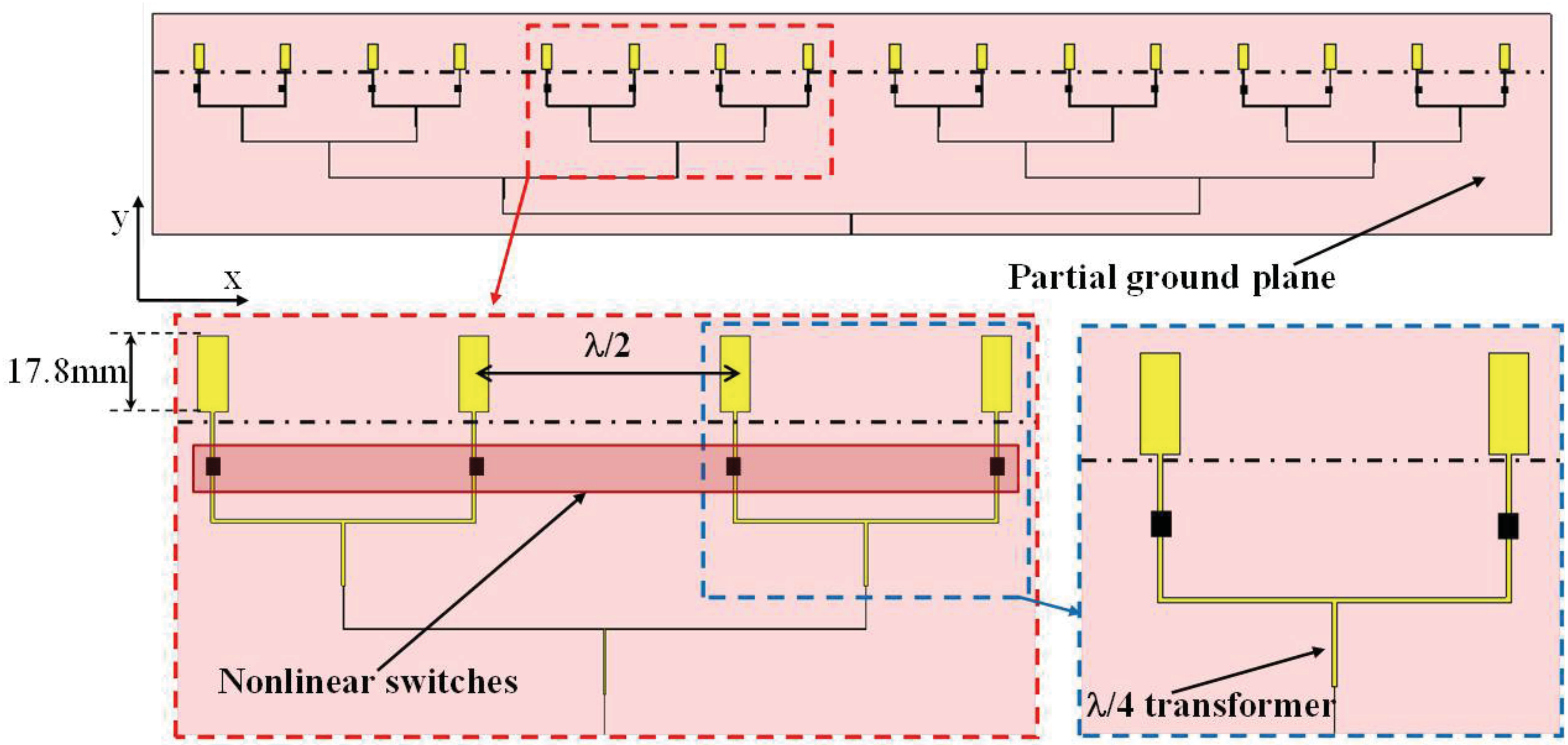
Field envelope at the fundamental harmonic

- $A_\theta^{(i)},\ A_\phi^{(i)}$ → ***EM data-base***
  - are the scalar components of the normalized field
  - easily evaluated by EM simulation
- For a given array: EM analyses are carried out ***once for all***

D. Masotti, P. Francia, A. Costanzo, V. Rizzoli, "Rigorous Electromagnetic/Circuit-Level Analysis of Time-Modulated Linear Arrays," *IEEE Trans. Ant. & Prop.*, vol.61, no.11, pp. 5465-5474, Nov. 2013.

16-MONOPOLE ARRAY DRIVEN BY MODULATED DIODES

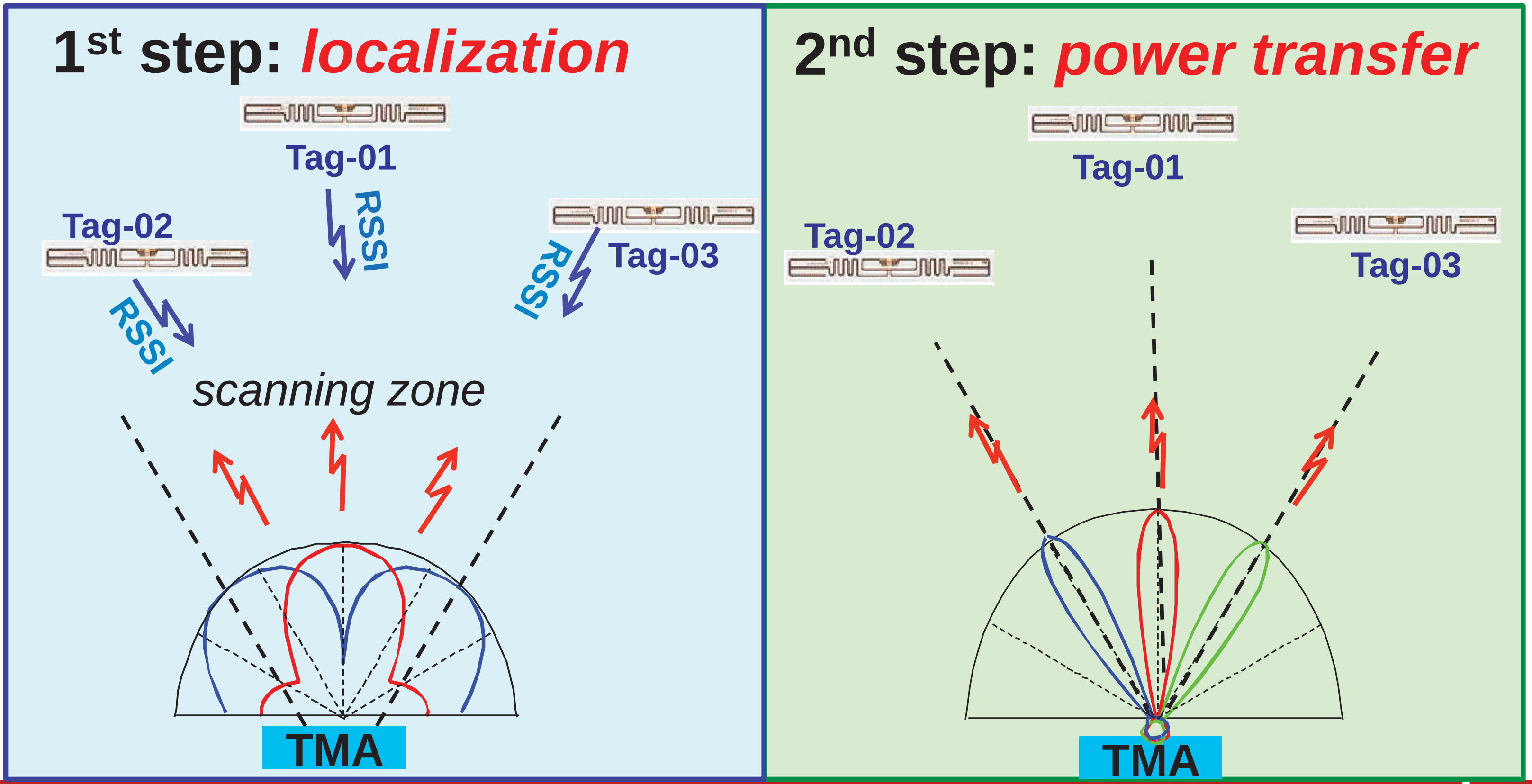
- 16-monopole planar linear array operating at f_0=2.45 GHz
- The substrate is a 0.635 mm-thick Taconic RF60A (e_r = 6.15, tand=0.0028 @ 10GHz)



Smart WPT BY TMA

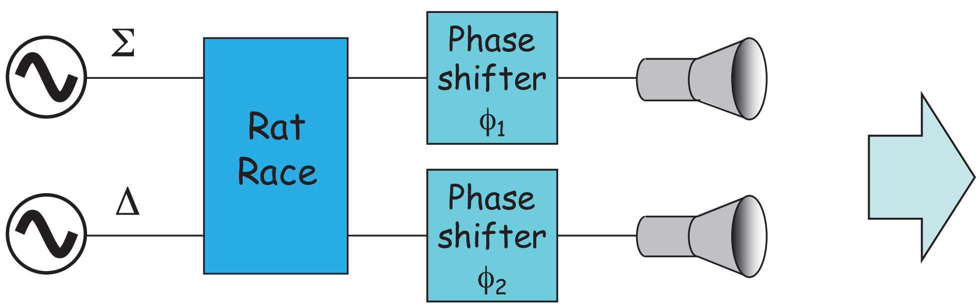
SMART WPT WITH TMA

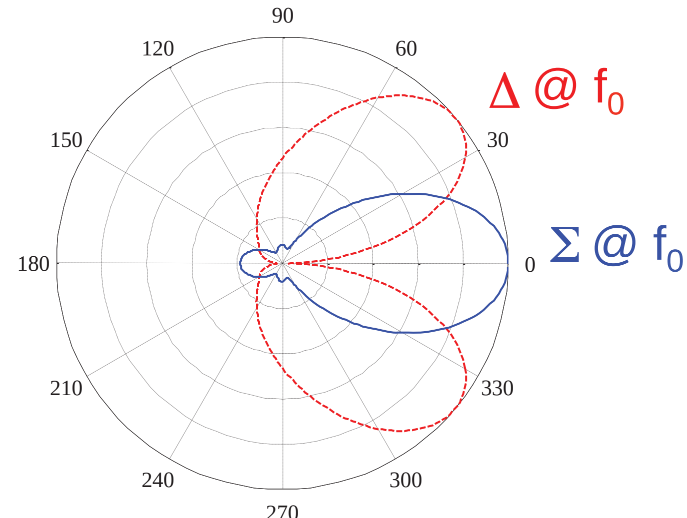
- The versatility of TMAs allows a ***smart transfer of power*** by means of a **two-step procedure**
- Scenario: room with randomly placed tagged objects



LOCALIZATION OF TAGS

- The RFID reader augmented by the ***Monopulse-RADAR capabilities:***
- By adopting a 2-element arrays: Σ and Δ radiation patterns are obtained from the *in-phase* (Σ) and *out-of-phase* (Δ) antennas excitation





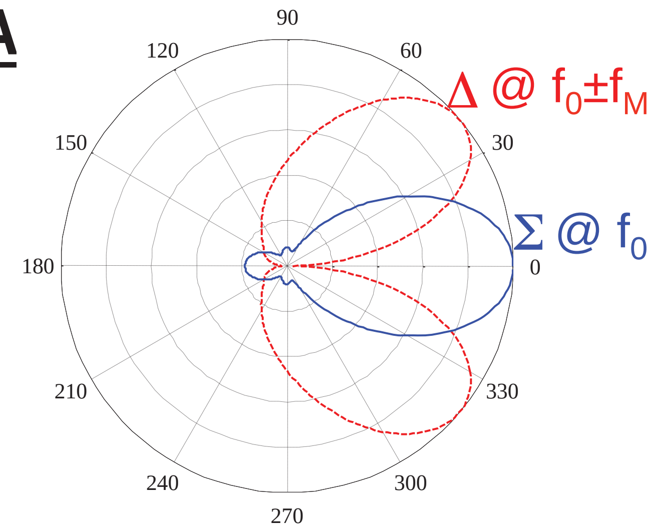
- Further feature ***beam-steering:***
  - by simultaneosly driving the proper phase shifts at the two antenna ports

M. Del Prete, D. Masotti, N. Arbizzani, and A. Costanzo, “Remotely Identify and Detect by a Compact Reader With Mono-Pulse Scanning Capabilities”, *IEEE Transactions on Microwave Theory and Techniques,* Vol. 61, No. 1, Part II, Jan. 2013, pp. 641-650

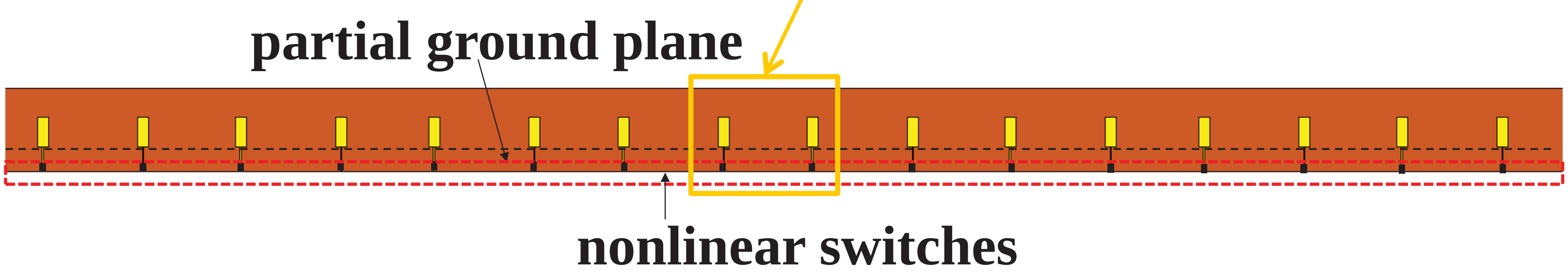
TAG LOCALIZATION BY MONOPULSE RADAR VIA TMA

- **1st step: *Localization of tags* with TMA**
  - By properly driving a two-element array it is possible to have the sum (Σ) pattern @ f_0 and the difference (Δ) pattern @ $f_0 \pm f_M$

A. Tennant, B. Chambers, “A Two-Element Time-Modulated Array With Direction-Finding Properties," *IEEE Antennas and Wireless Prop. Lett.*, vol. 6, pp. 64-65, 2007



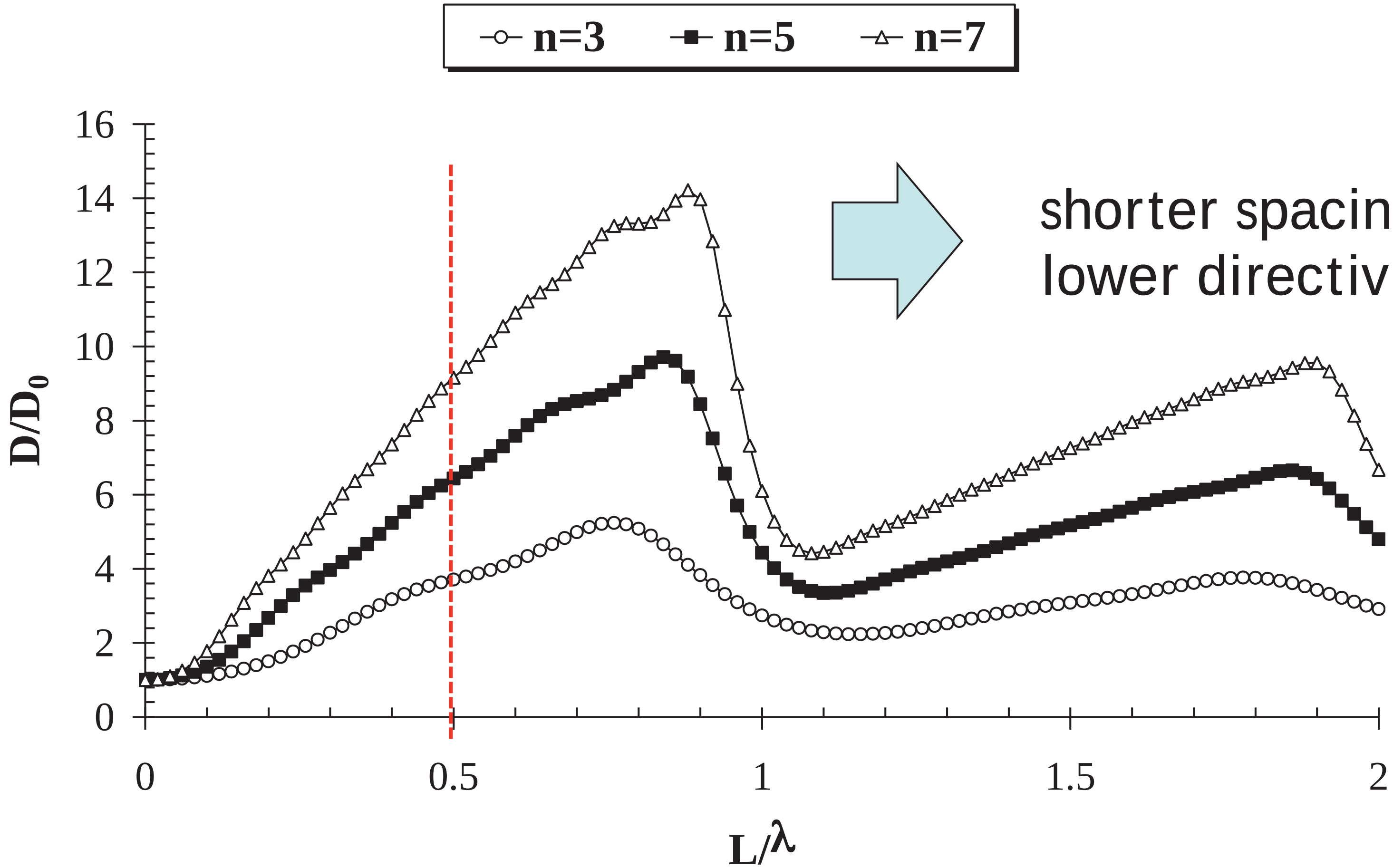
  - Only the ***two-inner-element sub-array*** is operating (by keeping the remaining 14 switches open)



D. Masotti, A. Costanzo, M. Del Prete, V. Rizzoli, "Time-Modulation of Linear Arrays for Real-Time Reconfigurable Wireless Power Transmission," IEEE Transactions on Microwave Theory and Techniques, vol.64, no.2, pp.331-342, Feb. 2016

TAG LOCALIZATION: ANTENNA ELEMENT SPACING AND DIRECIVITY

- Normalized directivity of an array of n *in-phase* (S) dipoles vs. element spacing L



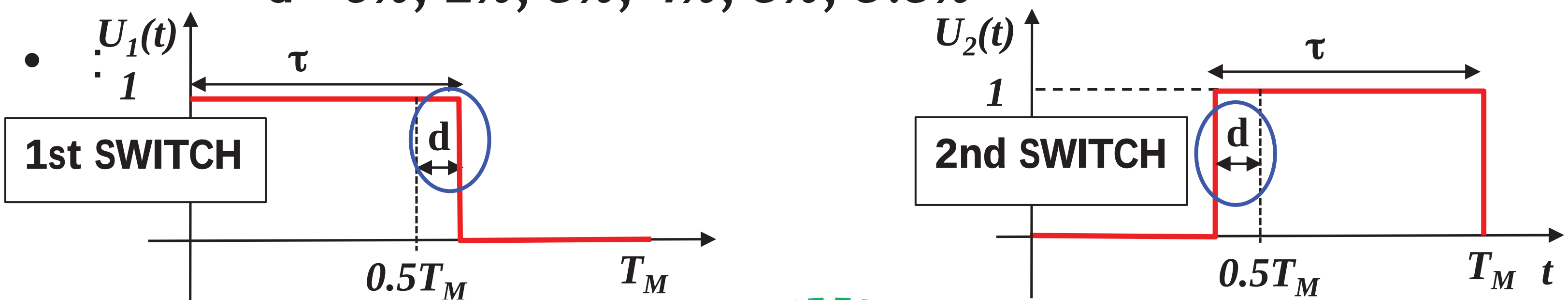
shorter spacing (L), allows lower directivity(D)

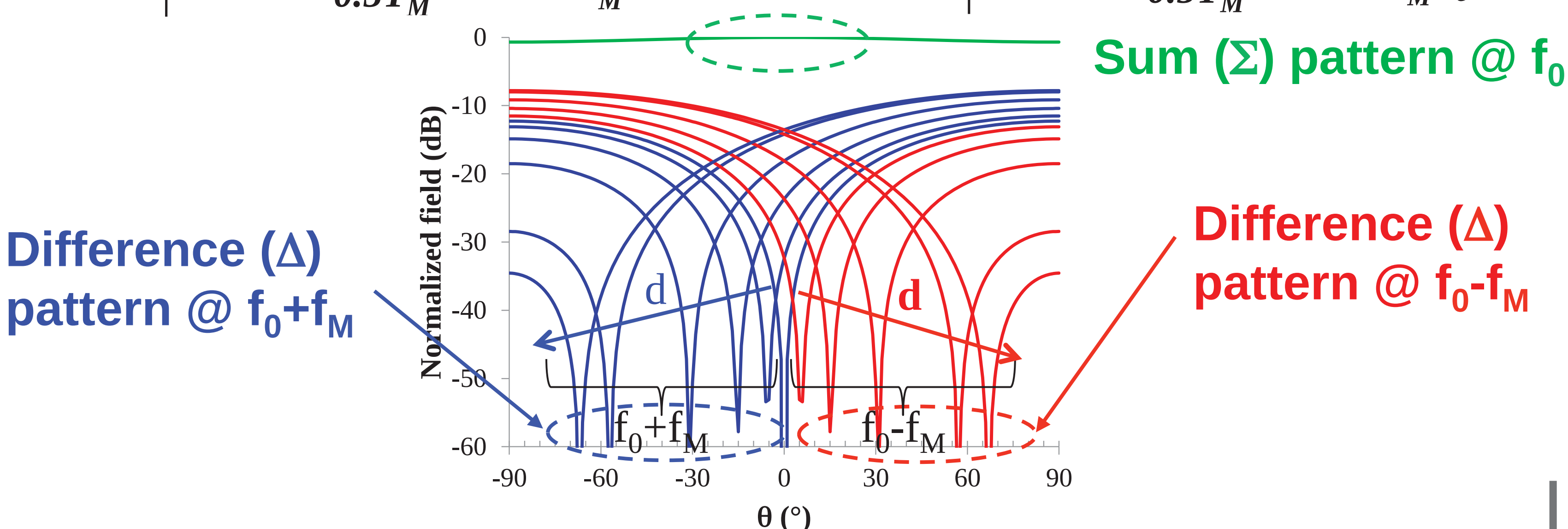
TAG LOCALIZATION CAPABILITY

- Array of two ***isotropic*** antennas with **λ/8 spacing**.
- **TUNABLE SEQUENCES:** ***Δ pattern*** is steared by varying ***d***

d= 0%, 2%, 3%, 4%, 5%, 5.5%

-

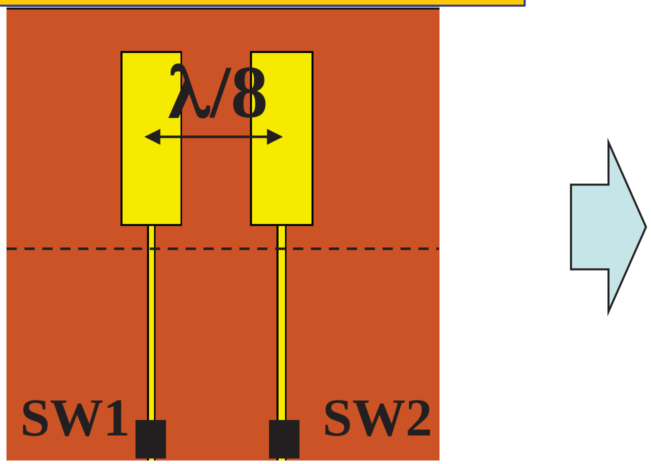




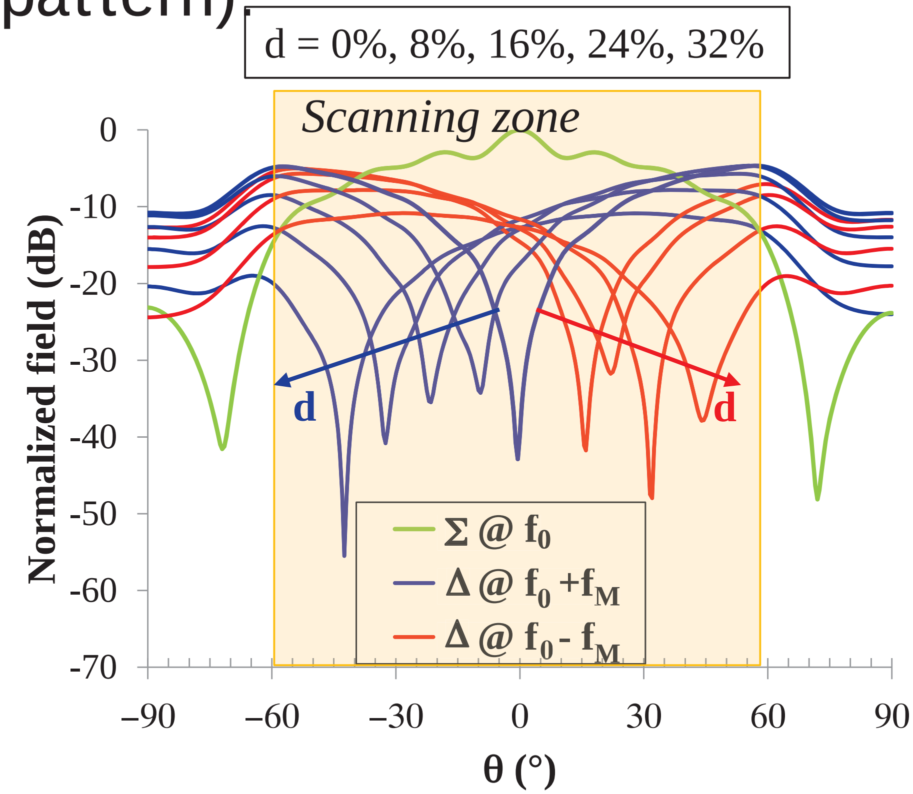
TAGS LOCALIZATION BY TMAs
(array of dipole $\lambda/8$ spaced)

- Array of two ***real, closer dipoles*** with tunable sequences (for flat and low-directive Σ pattern):

f_0=2.45 GHz, f_M = 25 kHz



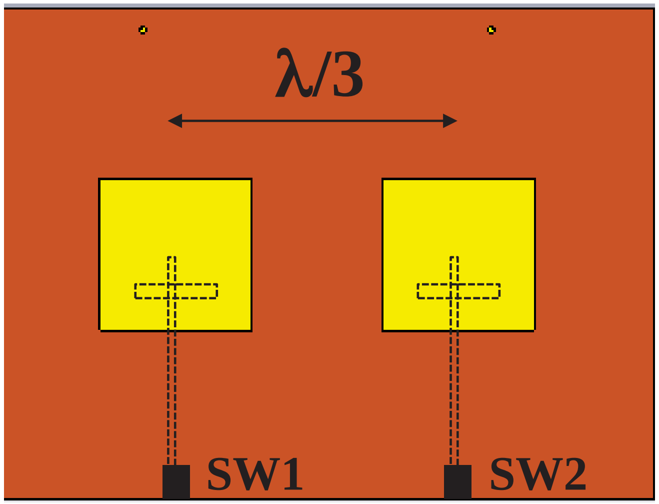
The substrate is a 0.635 mm-thick Taconic RF60A (ε_r = 6.15, tanδ=0.0028)

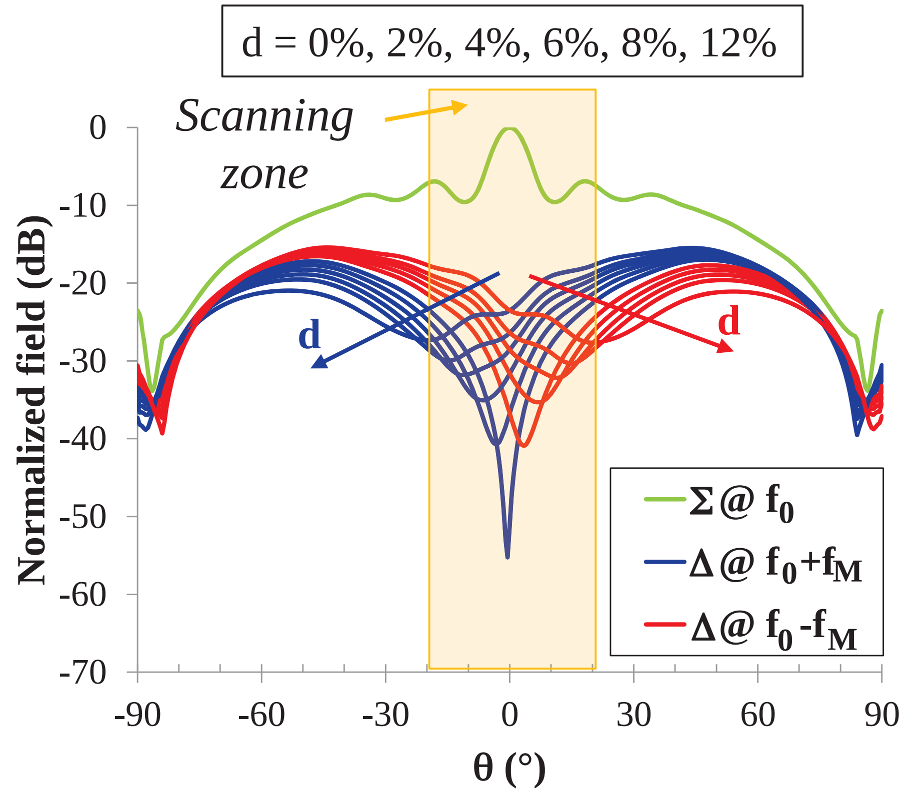


- Good scanning performance in θ∈[-60°:60°], but ***with larger d variations*** with respect to the theoretical prediction

TAGS LOCALIZATION BY TMAs
(array of patch λ/3-spaced)

- Array of two ***real patches*** with tunable sequences:



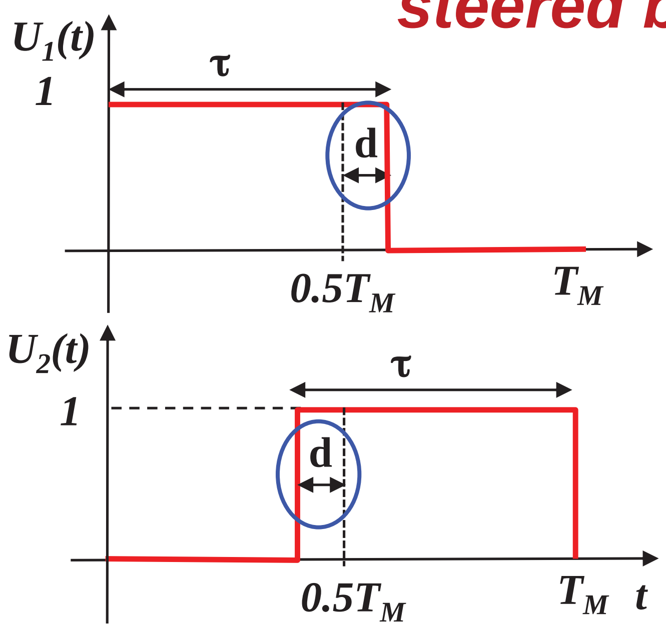


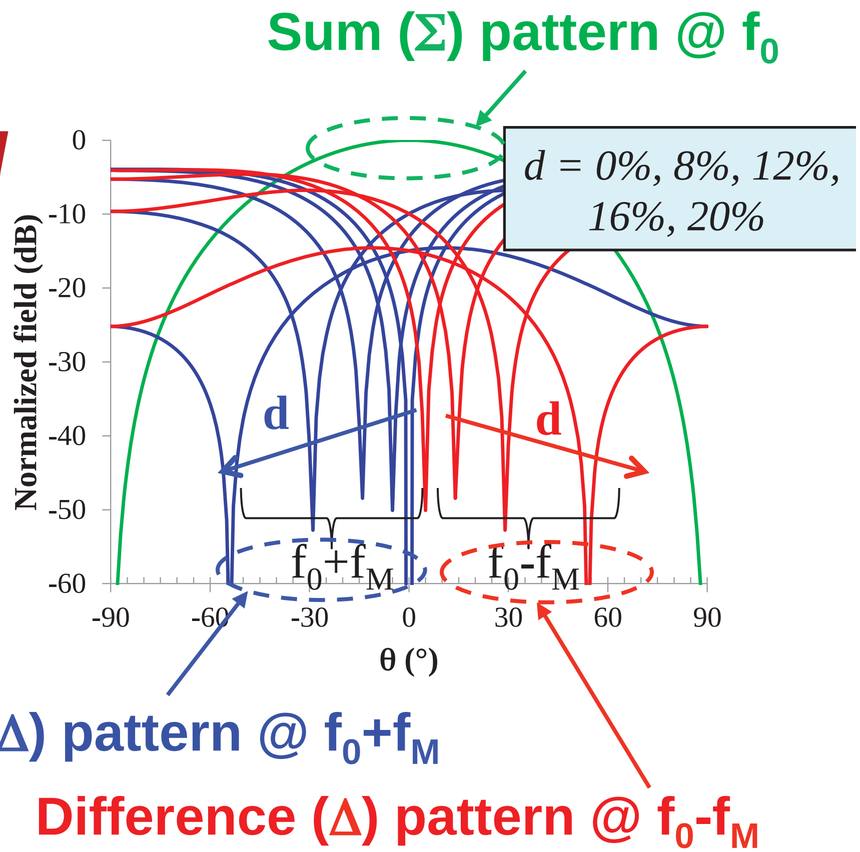
- Reduced scanning capabilities due to strong EM couplings

TAGS LOCALIZATION BY TMAs
(array of dipole λ/2 spaced)

- Array of two ***isotropic*** antennas with **λ/2 spacing**, driven by tunable sequences:

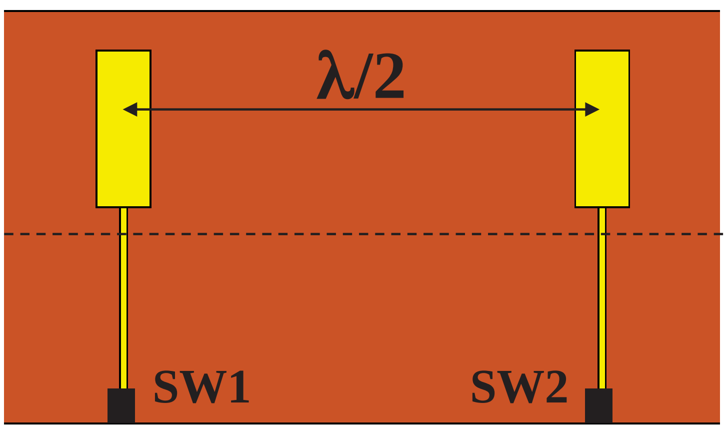
the Δ pattern can be steered by varying d

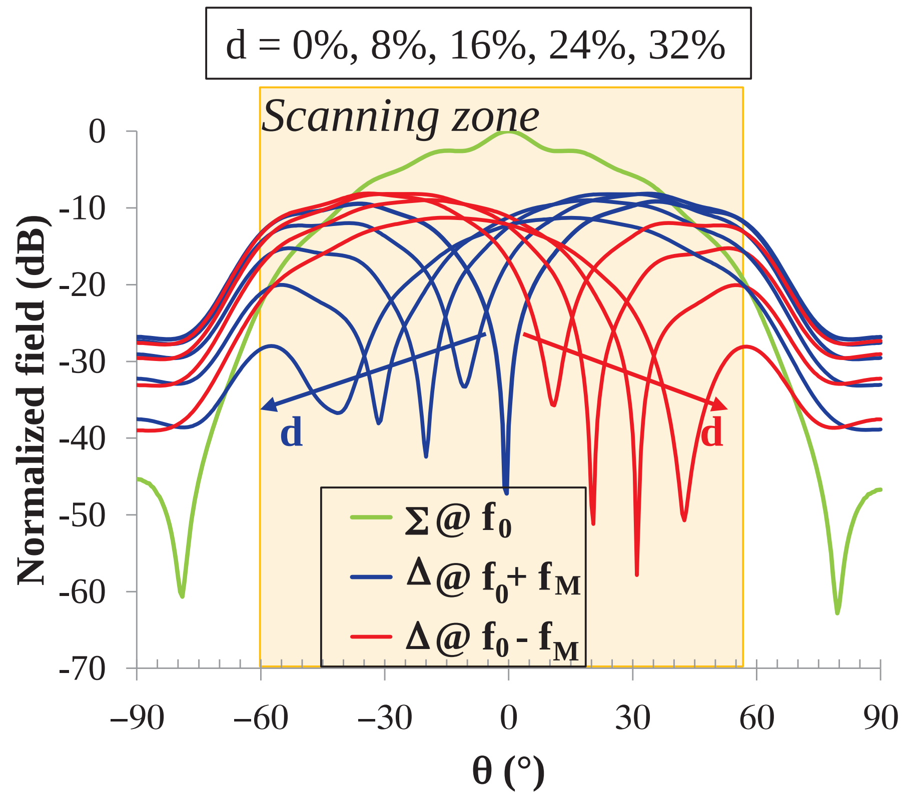




TAGS LOCALIZATION BY TMAs
(array of dipole λ/2 spaced)

- Array of two ***real dipoles* with λ/2 spacing** with tunable seq.

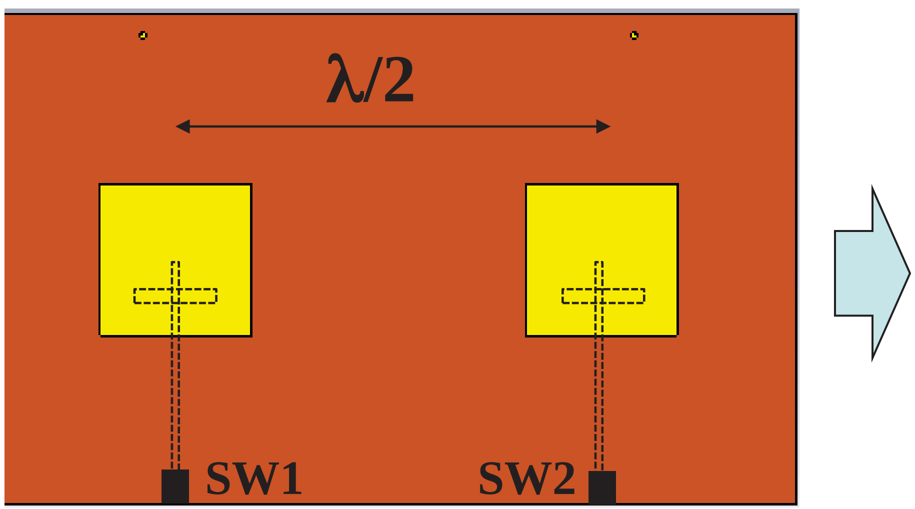


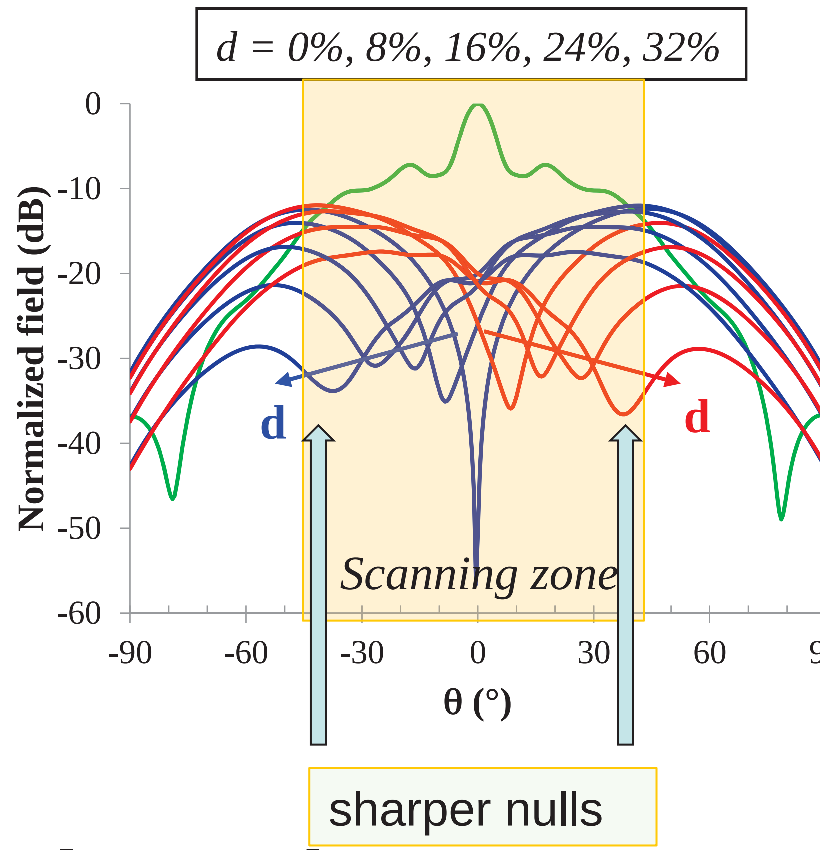


- Good scanning performance in θ∈[-60°:60°]

TAGS LOCALIZATION BY TMAs
(array of patches λ/2 spaced)

- Array of two ***real patches* with λ/2 spacing** with tunable seq.





- Good scanning capabilities in θ∈[-40°:40°]

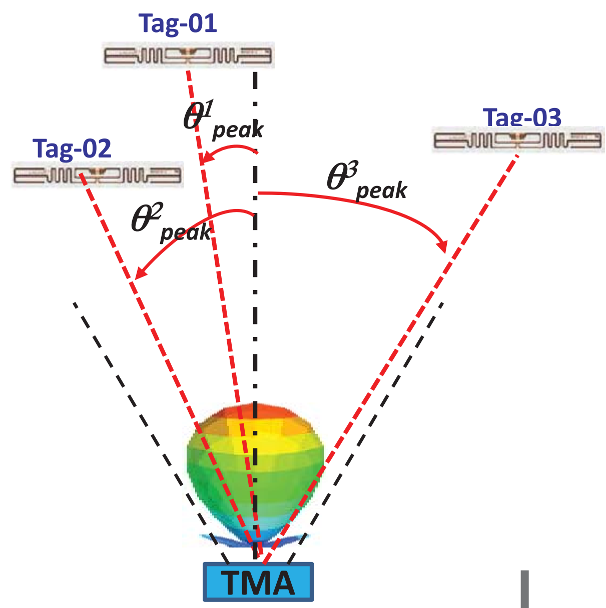
TAGS LOCALIZATION PROCEDURE

- The sharp nulls of the steered D patterns allow high resolution in the tags detection
- The backscattered Received Signal Strength Indicators (RSSI), due to the Σ and Δ patterns, can be suitably combined to build the ***Maximum Power Ratio (MPR)***

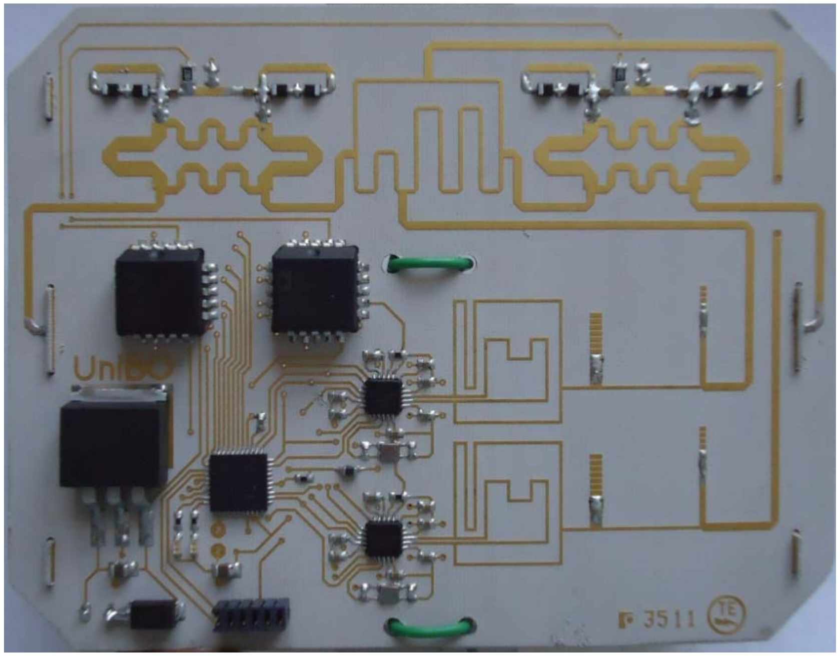
$$MPR(\theta) = \Sigma^{dB}_{RSSI}(\theta) - \Delta^{dB}_{RSSI}(\theta)$$

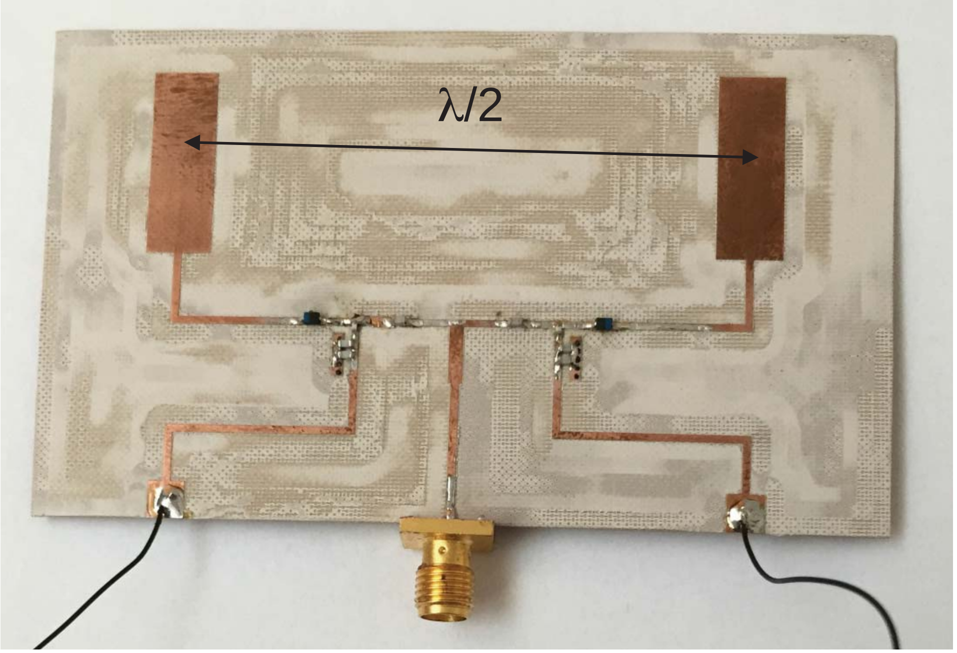
θ^{i}_{peak}; $i=1, \ldots, N_{tag}$

List of recordered tags position



ARRAYS FOR LOCALIZATION: A COMPARISON



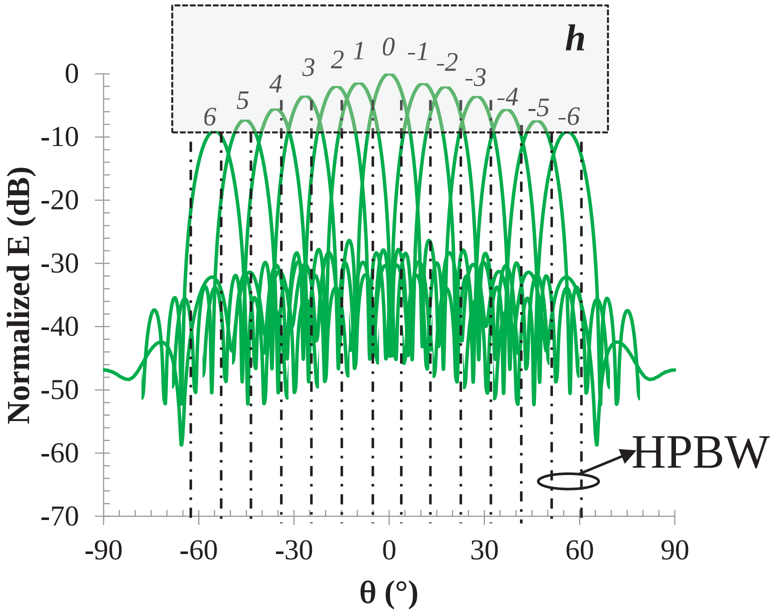


RFID READER WITH MONOPULSE RADAR CAPABILITIES

TMA-BASED IMPLEMENTATION OF THE RFID READER

TRANSFER TO THE TAGS

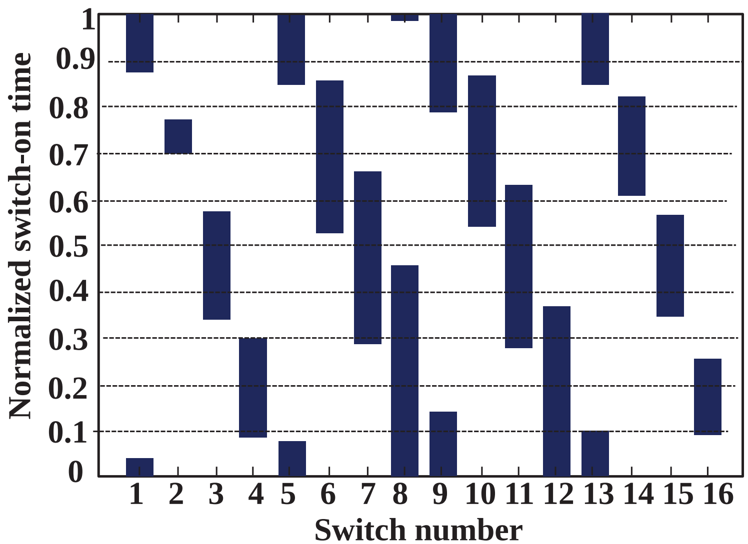
- **2° step:** *Transfer of power to tags*
  - ***The whole 16-element array*** is driven by proper ***pre-loaded control sequences*** involving all the switches
  - Possible <u>decision rule</u>:
    - split the scanning region ($\theta \in [-60° \div 60°]$) into sectors of amplitude equal to the half power beam width (HPBW)
    - for each θ_{peak} falling in the sector centered around θ_{HPBW}, the pre-loaded control sequence pointing the **proper harmonic** to the θ_{HPBW} direction is used

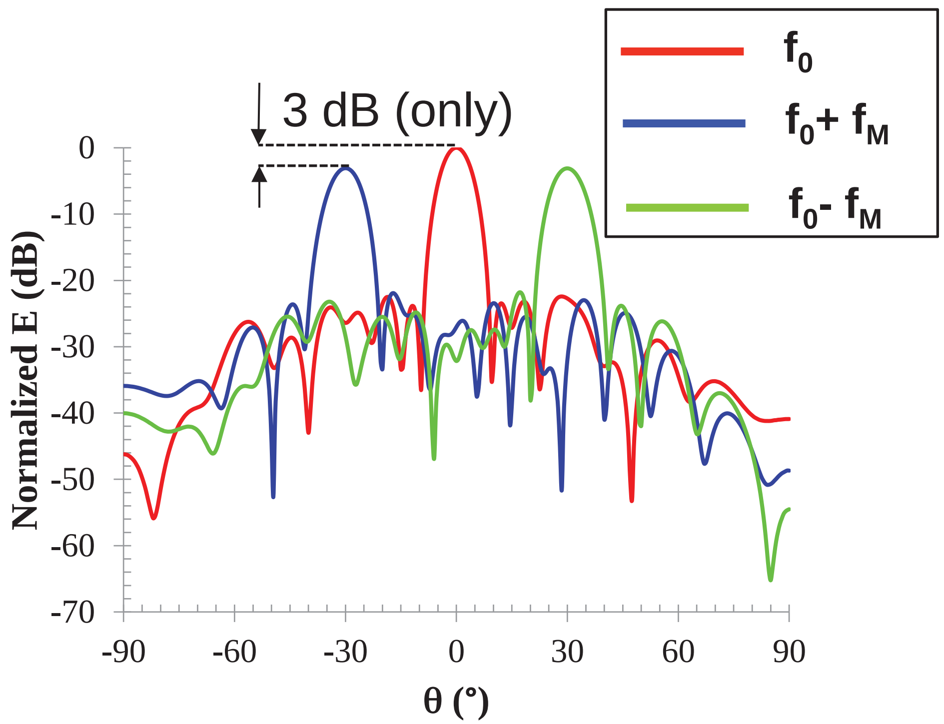


SIMULTANEOUS POWERING OF THREE TAGS

- In case of θ_{peak} falling into the sectors centered around θ_{HPBW} = -30°, 0°, 30°

L. Poli, P. Rocca, G. Oliveri, A. Massa, "Harmonic beamforming in time-modulated linear arrays through particle swarm optimization", *IEEE Trans. Ant. & Prop.*, vol. 59, no. 7, pp. 2538-2545, July 2011

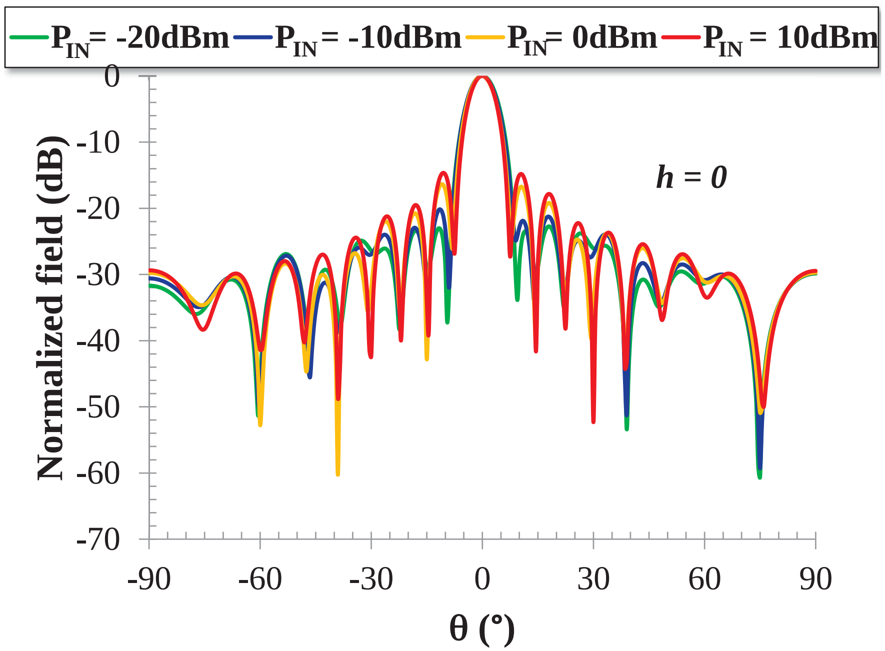


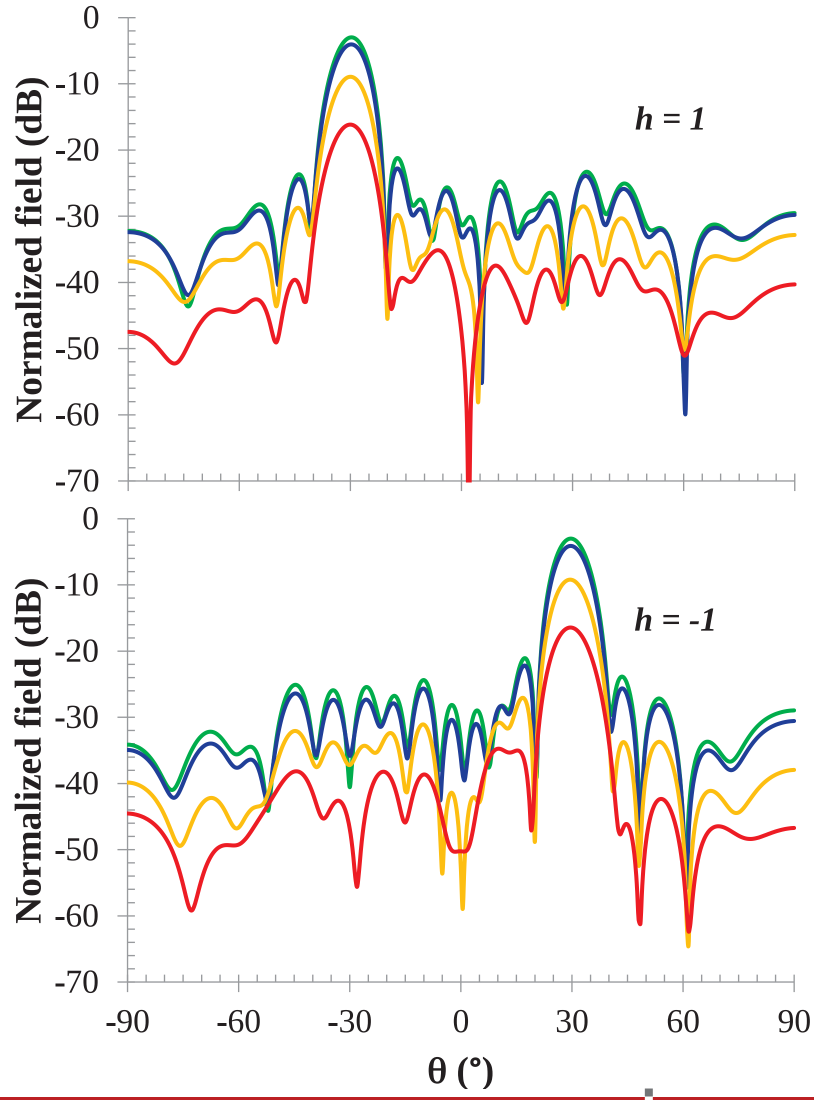


Simultaneous powering of 3 tags

POWER HANDLING ISSUES

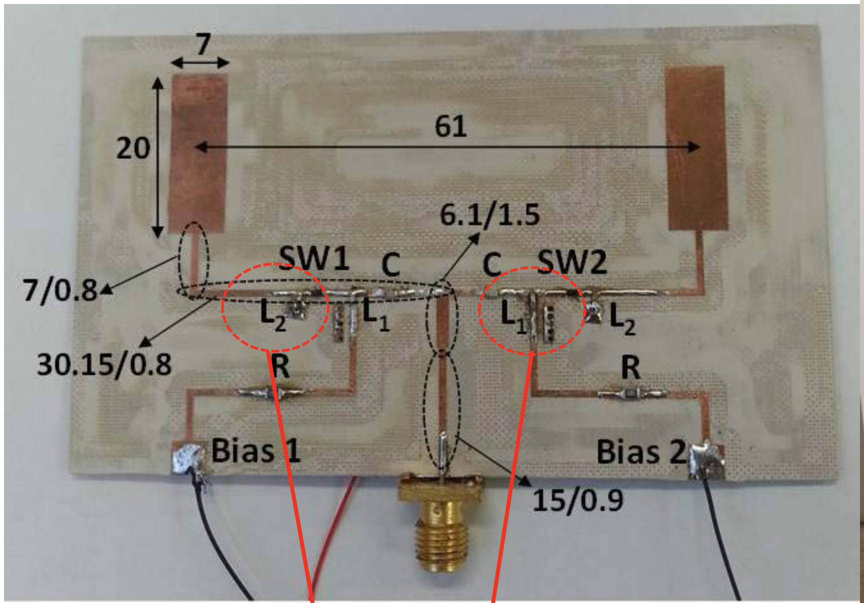
- Schottky diode (Skyworks SMS7630-079) used as the switching element



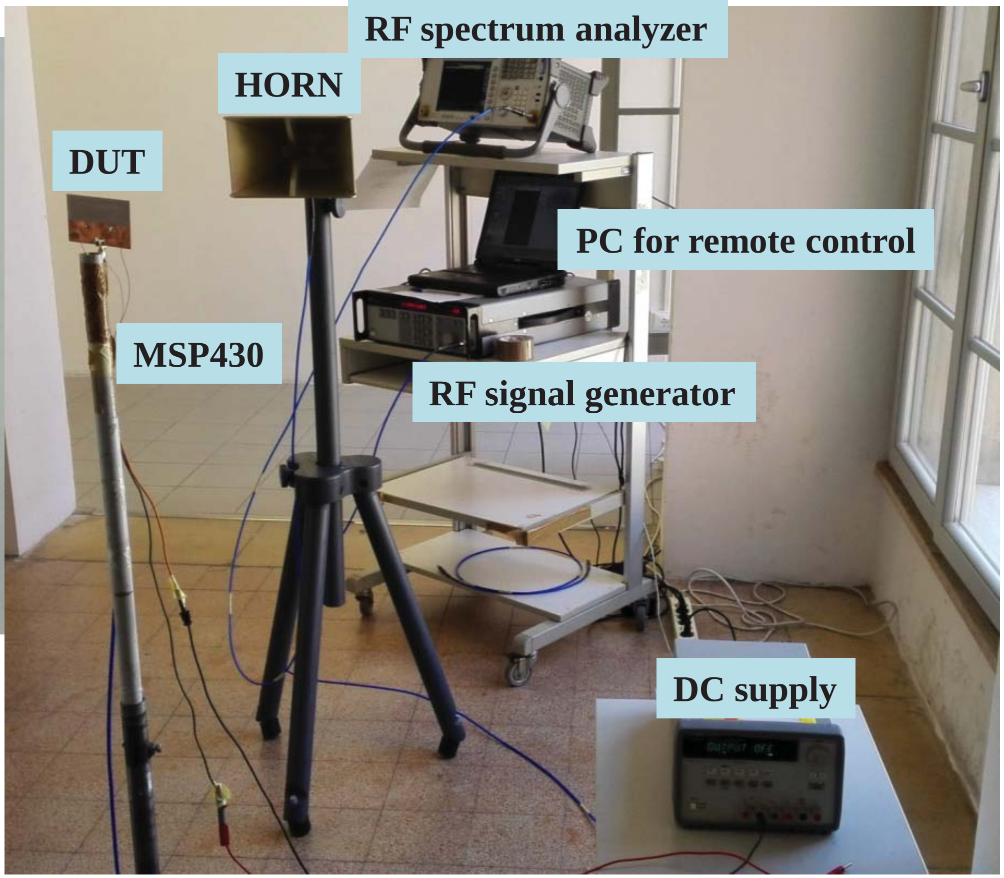


For the medium-power diode in use, the input power limit is about 0 dBm ➡ high-power PIN diodes (e.g. Infineon BAR64-02V)

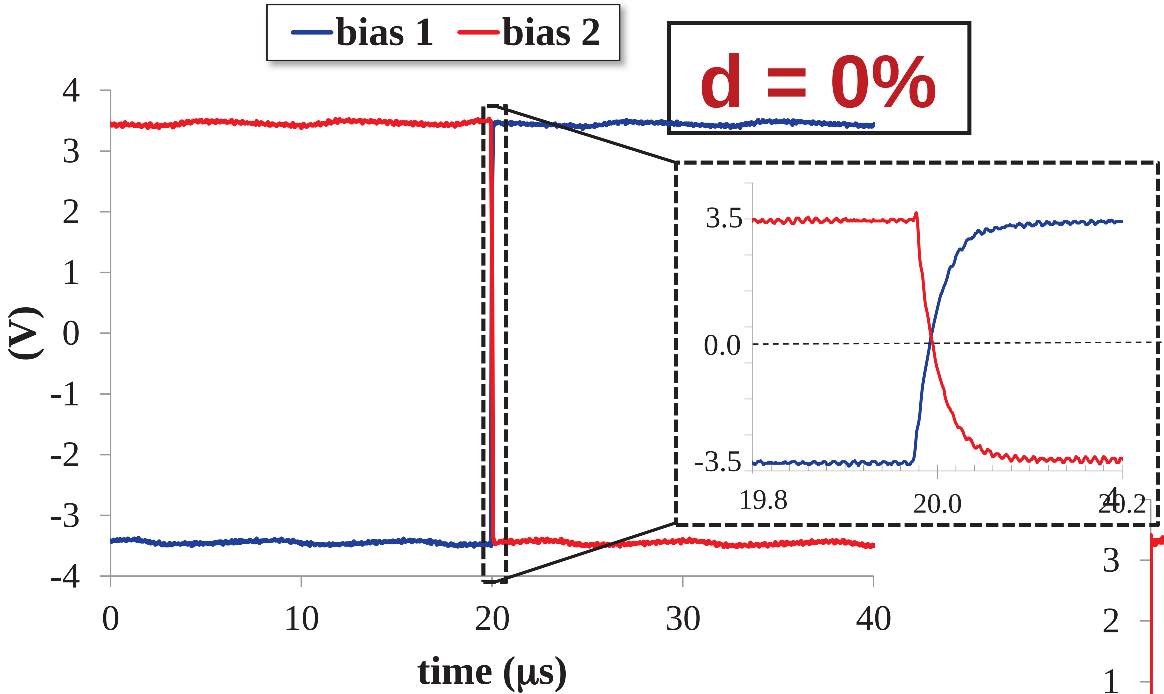
PROTOTYPE AND SET-UP

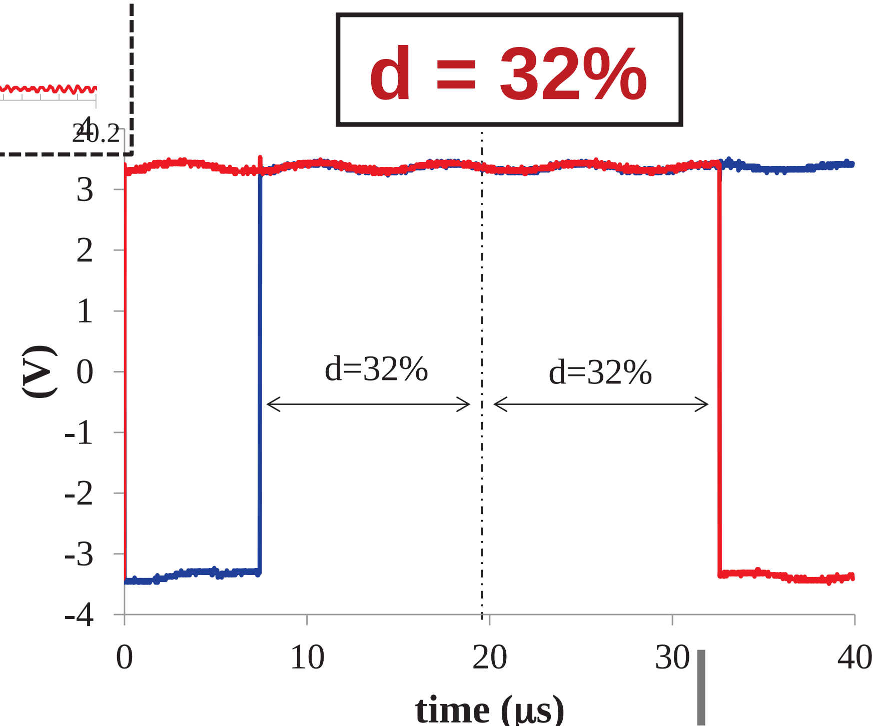


Medium-power Schottky diodes
Skyworks SMS7630-079

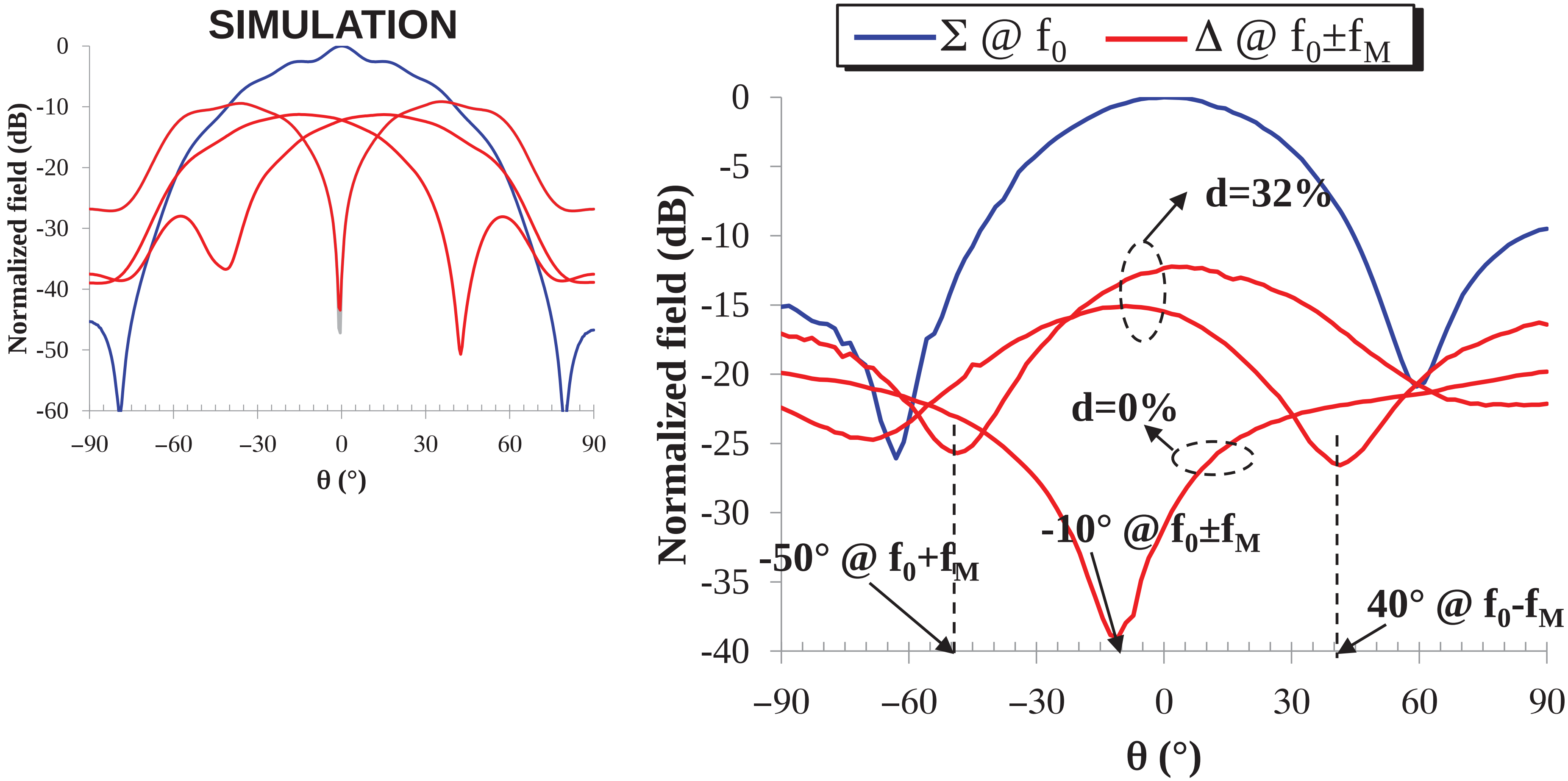


REAL WAVEFORM SEQUENCES FOR LOCALIZATION



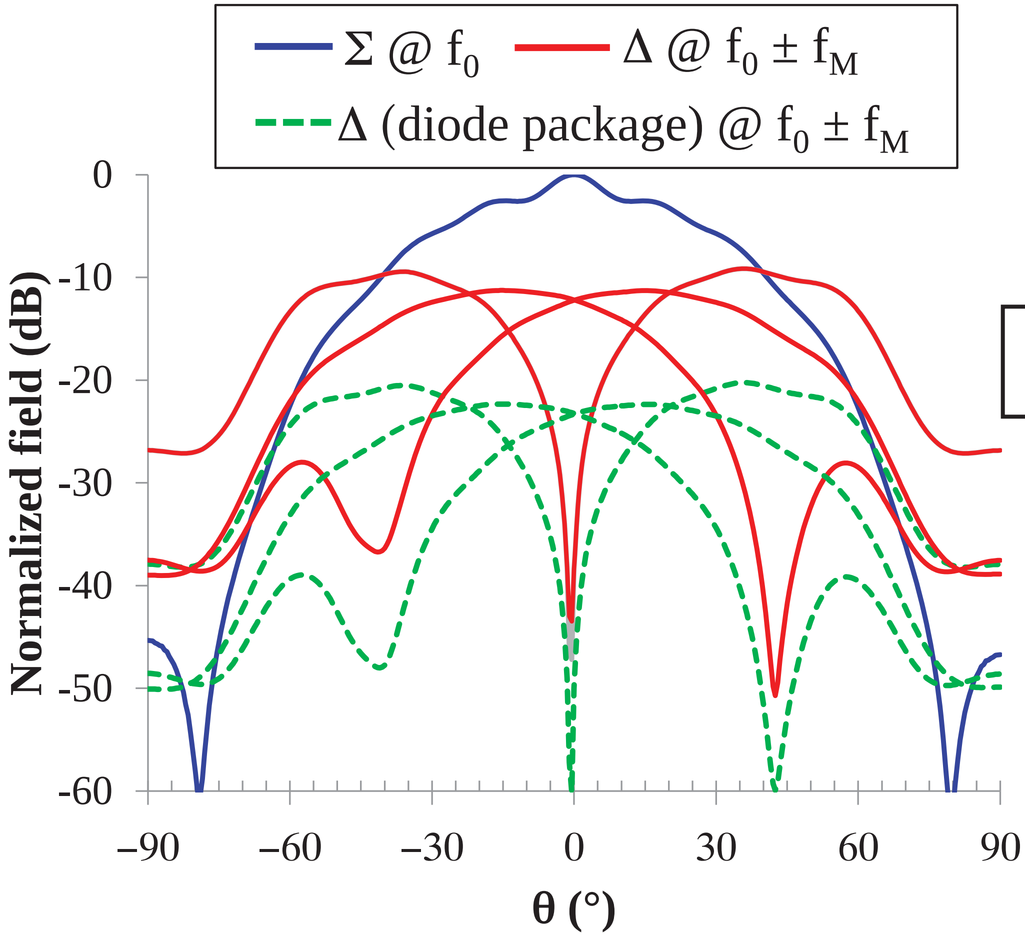


MEASURED RADIATION PATTERNS



- Slight asymmetry probably due to an asymmetry of the circuit
- Lower Δ patterns strength w.r.t. simulation

Simulated radiation patterns



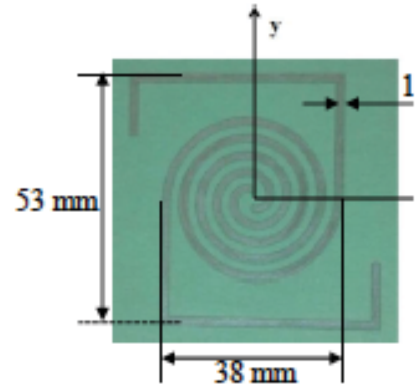
d = 0%, 32 %

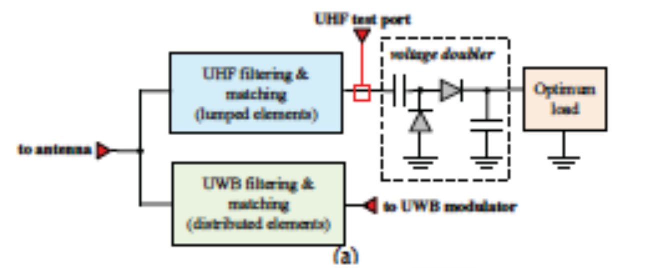
- Diode package parasitics responsible for an alternative path for RF signal to antenna ports ➡ not perfect control

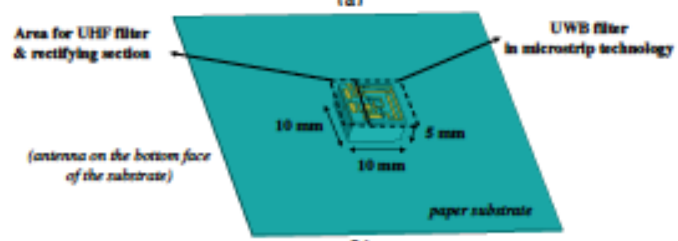
Perspectives : GRETA

On paper UWB/UHF Antenna design and rectifiers

Loaded with the UWB and UHF backscatter modulator and the energy-harvesting block



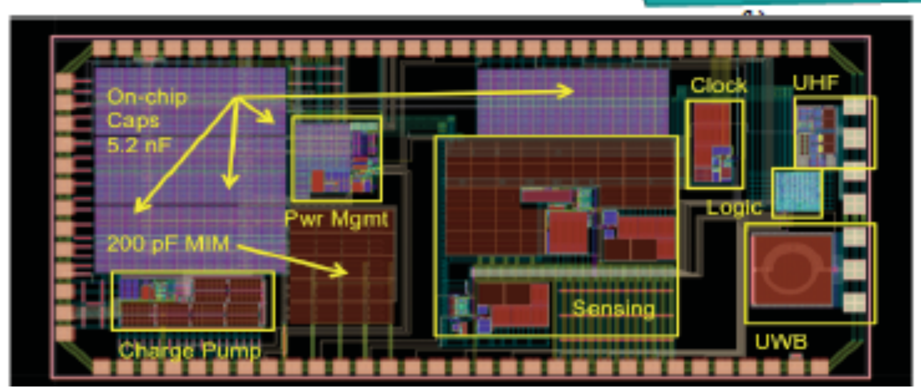




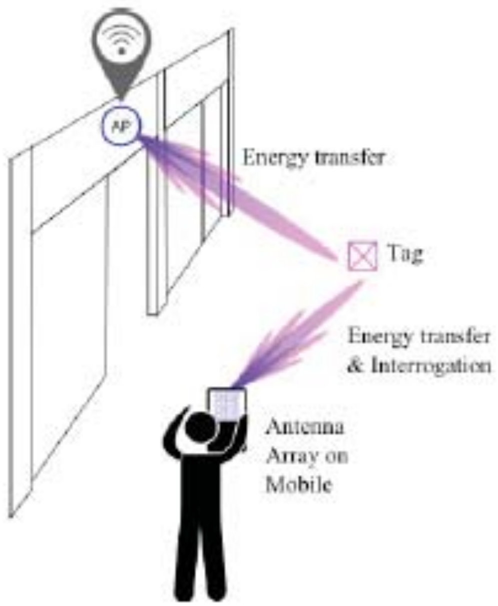
The "GRETA" chip

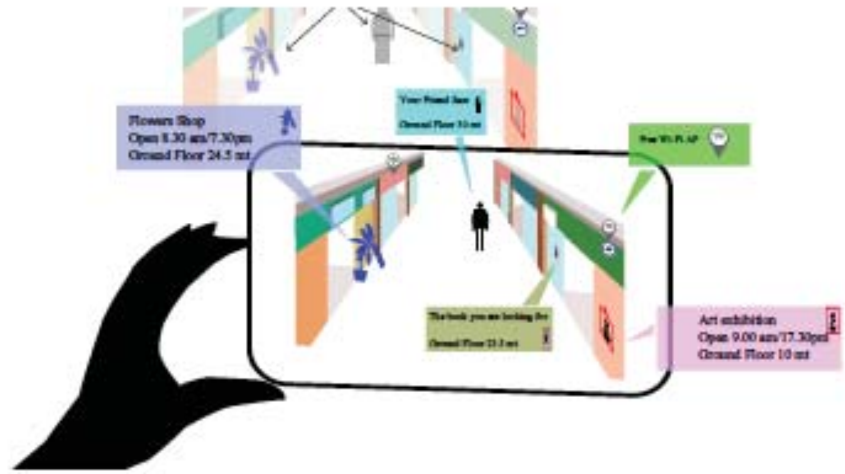
Layout of the custom chip under test developed at Univ. Bologna containing:

- UWB backscatter modulator,
- energy harvesting unit at UHF,
- power management unit,
- control logic.



PERSPECTIVES





RFID/RTLS integration in smartphones:

- Millimeter wave massive antenna arrays
- Efficient energy transfer mechanisms to energize passive/active tags
- Single node localization

D. Dardari, et al. "The future of Ultra-Wideband localization in RFID," in 2016 IEEE International Conference on RFID, Orlando, USA, May 2016

CONCLUDING REMARKS

- Need for solutions to integrate RFID, RTLS and energy harvesting capabilities for IoT applications.

- Simple, low-cost, light-weighted solutions for on-demand RF energy transfer
  - Reader augmented the a monopulse RADAR antenna enabling object detection and selection for efficient power "*on demand*" a
  - Time-modulated arrays demonstrate an unreachable, ***almost real-time*** reconfiguration.

- The ease of implementation of the TMAs (no phase shifters) makes them a potential candidate for ***smart, pervasive WPT solutions***

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http://www.dei.unibo.it/en/research/research-facilities/Labs/rfcal-rf-circuit-and-antenna-design-lab