International School on: ***Electromagnetics and emerging technologies for pervasive applications: Internet of Things, Health and Safety***

# Intentional Wireless Power Transmission via Time-modulated Arrays


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WIPE

COST IC1301

**IC1301 – COST School**

**April 18th – 20th, 2016**

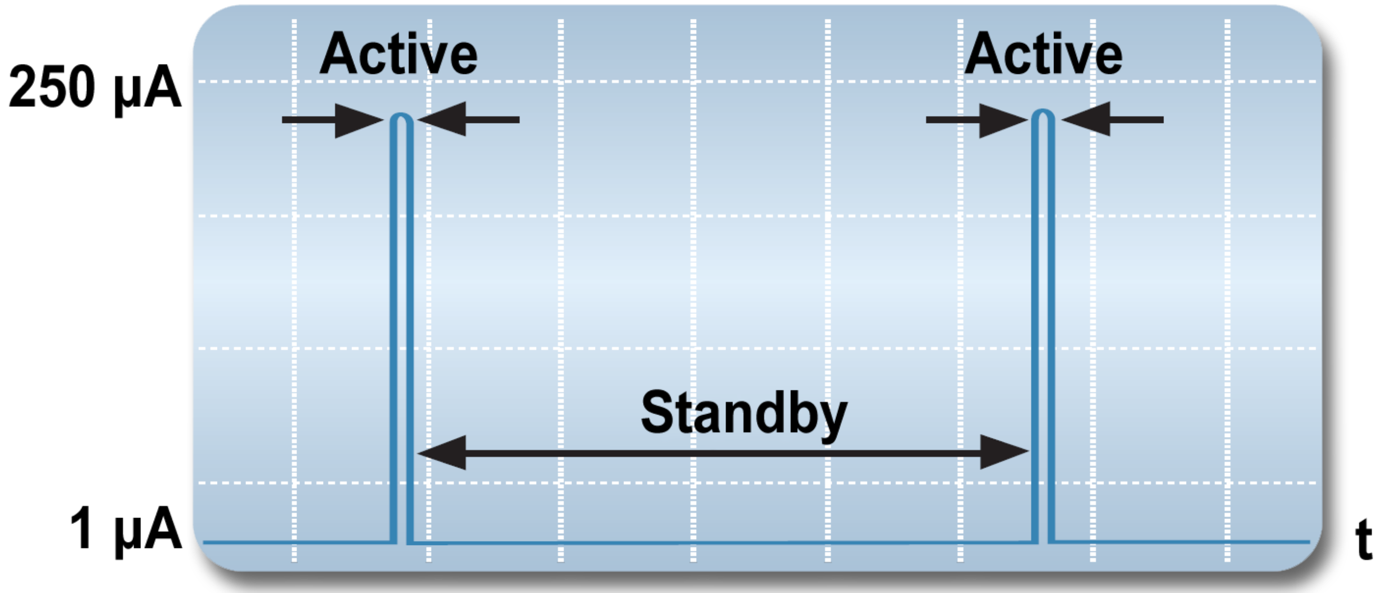
# Outline

- From the **reception** point of view
  - Need for energy collection from ***environmental*** and ***intentional*** RF sources → RECTENNAS
- From the **transmission** point of view:
  - Need for agile radiating systems
  - ***Time-modulated arrays (TMAs)***: a new and highly reconfigurable family of radiating systems
  - Overview of ***TMA*** circuital description by a combination of nonlinear CAD and electromagnetic simulation
  - Exploitation of TMA real-time, multi-frequency beam-forming for ***Smart Wireless Power Transmission***

# RF energy collection

# Need for *low* energy

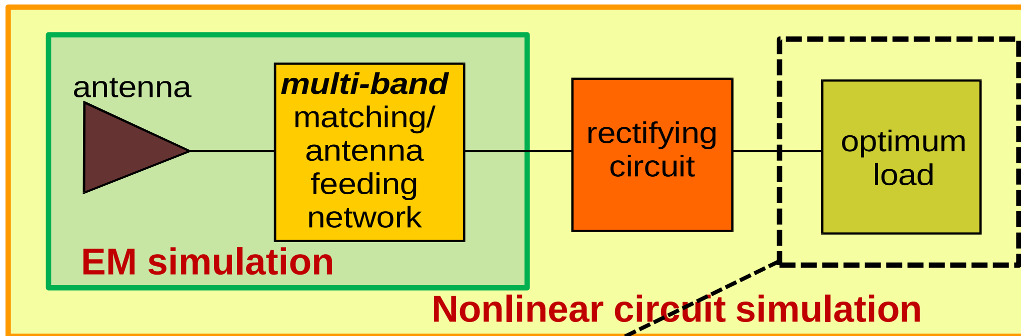
- Many applications can be supported by small amounts of power (***from a few μW to a few hundreds of μW***),



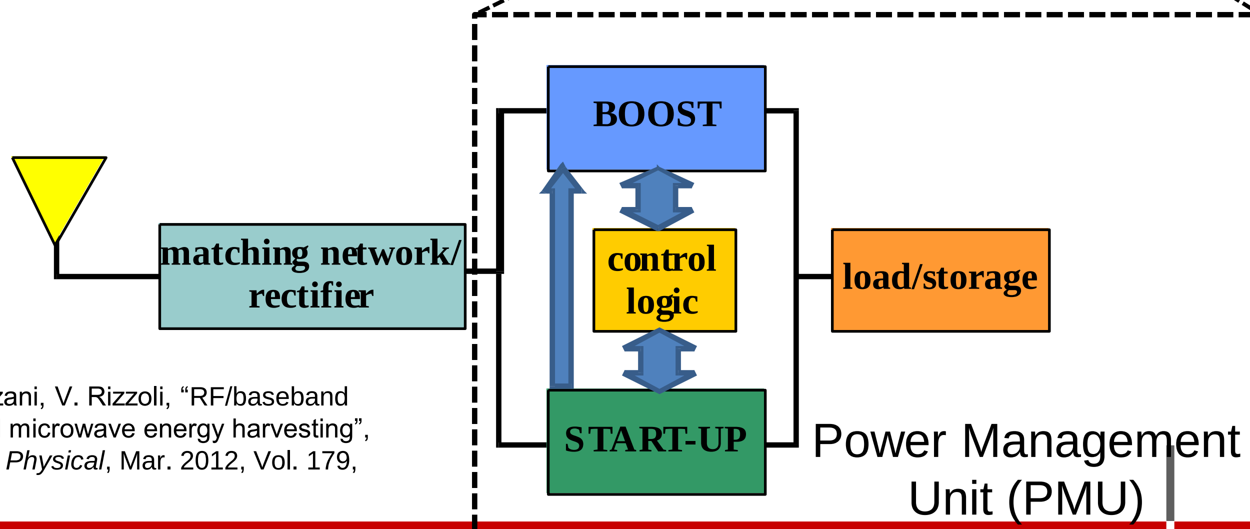

***ultra-low power*** microcontrollers and sensors requiring power consumption few times per day

# RECTENNA

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



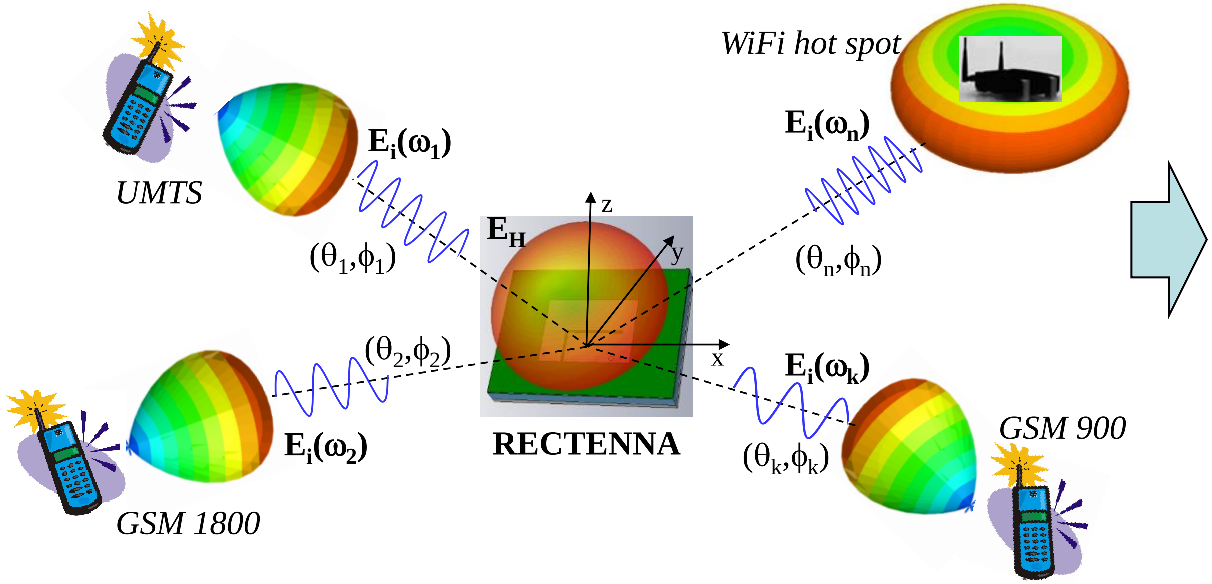

  - 2nd level design




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 EH

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




***collected power in the low μW range*** (even without considering channel dispersion and antennas misalignment effects)

- 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

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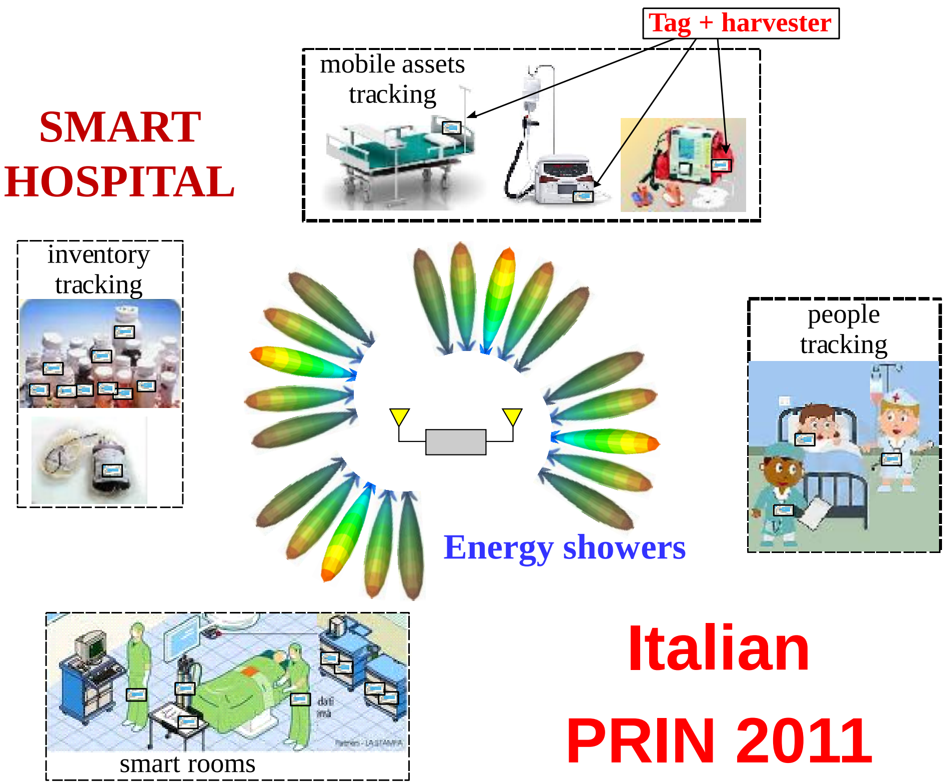
- RECTENNA for Wireless Power Transfer: exploits ***intentional and dedicated*** RF sources (***"Energy showers"***)




***collected power in the high $\mu$W range*** (considering realistic scenarios)

**Italian PRIN 2011**

GRETA

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

# Rectenna for EH

- Rectenna for EH requirements:

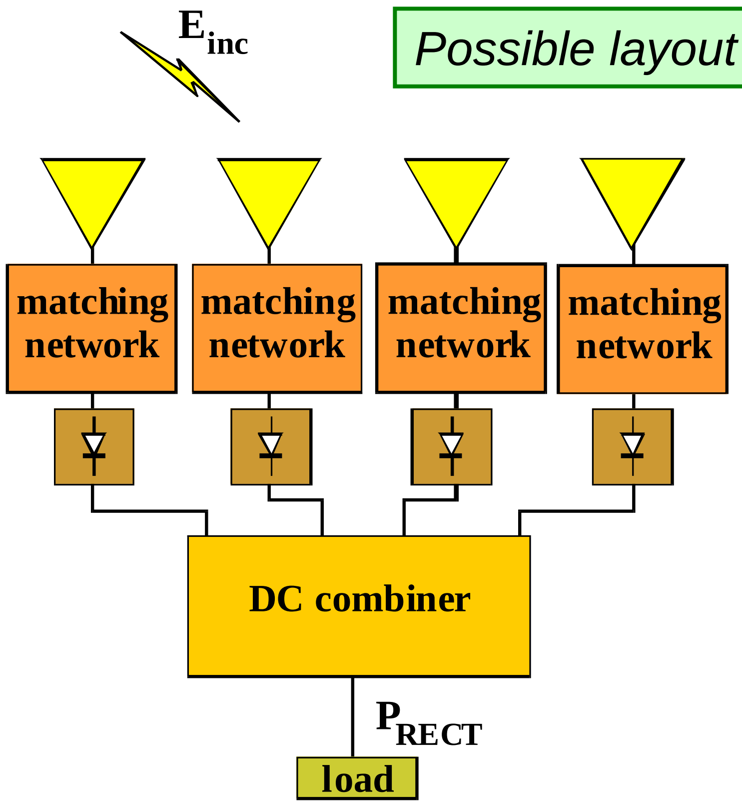
**RF EH**: **UNKNOWN info:**

- 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

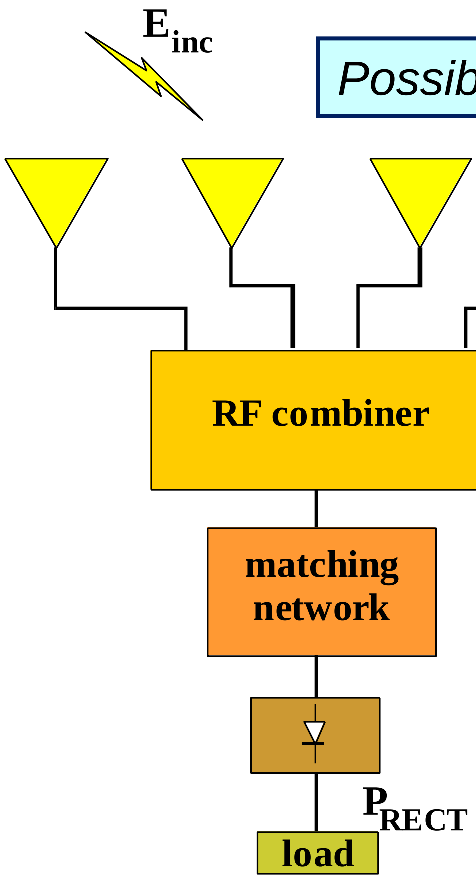
- Rectenna for WPT requirements:

**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*

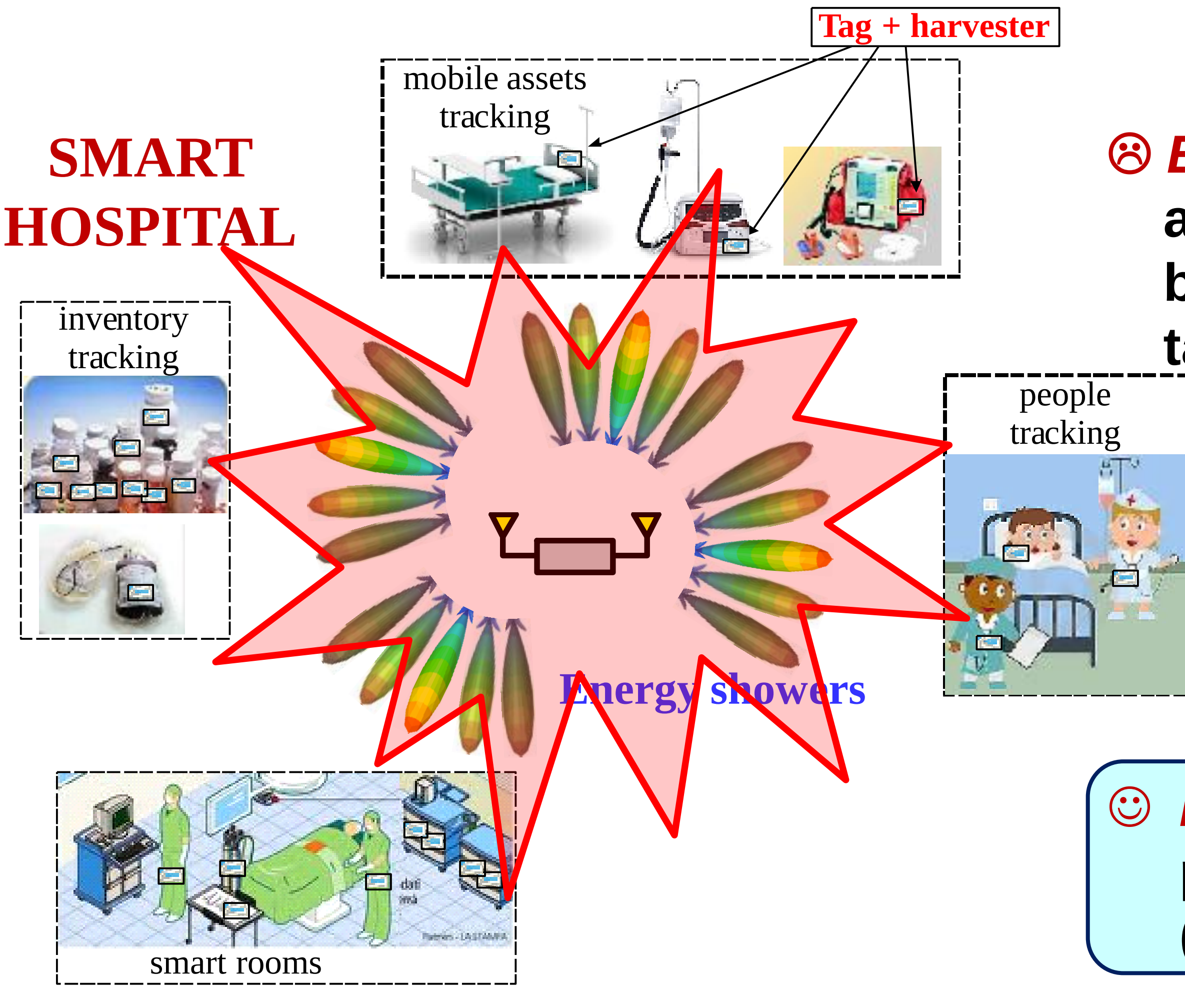



**Antenna array & single rectifier**

# RF energy transmission

# How to send power?

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




☹ ***Energy-unaware solution:*** **almost omnidirectional behavior (highly crowded-tag scenario)**

☺ ***Energy-aware solution:*** **precise and selective (multi-tag scenario)**

# Agile Transmitters

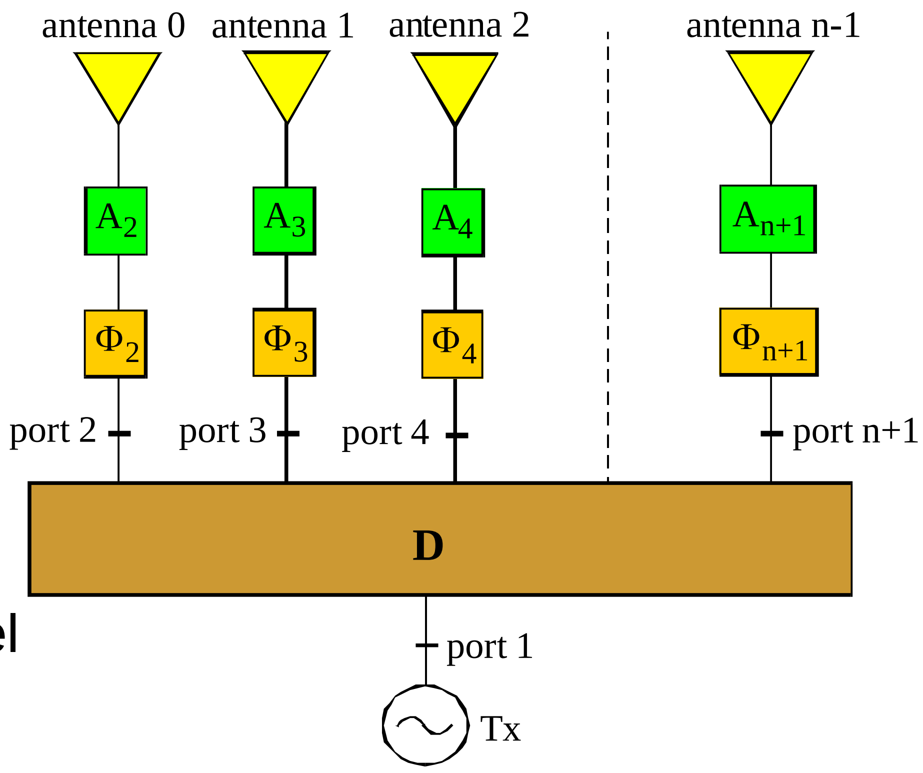
- A modern and agile radiating system has to be:
  - Able to point in selected directions
  - Highly reconfigurable
  - Easy to be designed
- Available solutions:
  - ***PHASED ARRAYS***
  - ***RETRODIRECTIVE ARRAYS***
  - ***SERIES-FED ARRAYS***
  - ***TIME-MODULATED ARRAYS***

# PHASED array

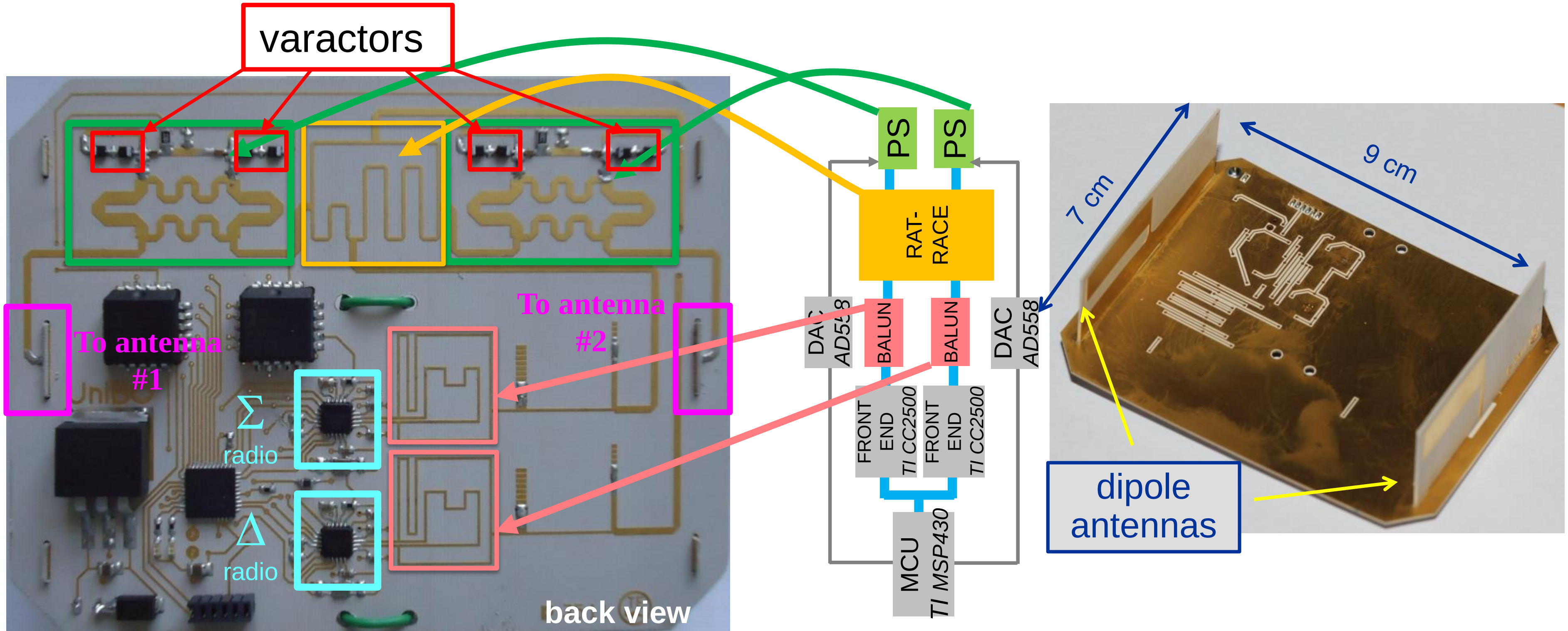
- ***PHASED ARRAY***
  - D: n-way symmetric power divider
  - $\Phi_i$: i-th phase shifter, electronically controlled by a voltage signal (Vi)

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

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



# Phased array example



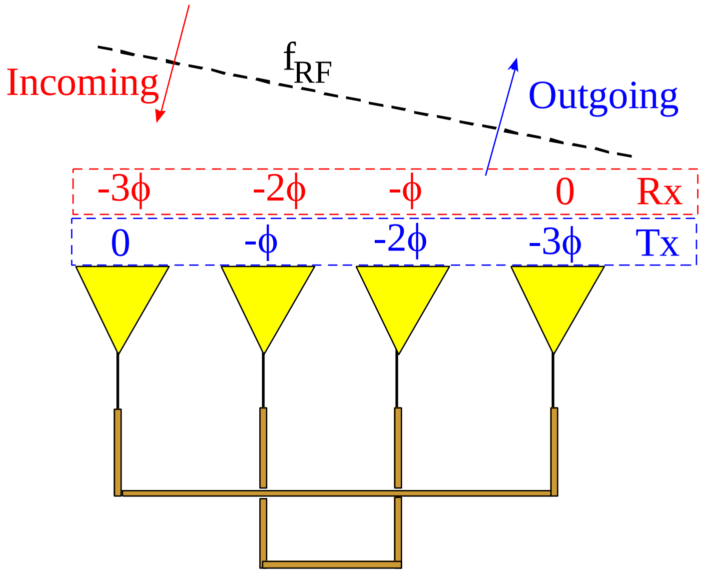

M. Del Prete, D. Masotti, N. Arbizzani, and A. Costanzo, "Remotely Identify and Detect by a Compact Reader With Mono-Pulse Scanning Capabilities", *IEEE Transactions on Microwave Theory and Techniques,* Vol. 61, No. 1, Part II, Jan. 2013, pp. 641-650

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

# RETRODIRECTIVE array

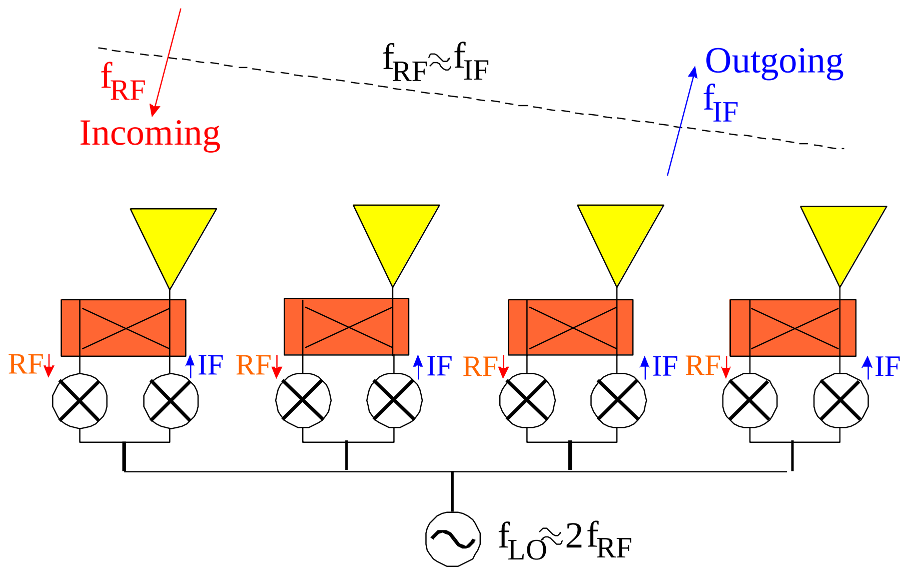
- ***RETRODIRECTIVE ARRAY:*** reflects an incident RF signal back in the direction of arrival. For applications with *relaxed* pointing accuracy and automatic beam forming

  - Van Atta RDA




  - Proper lines length provides proper phase condition

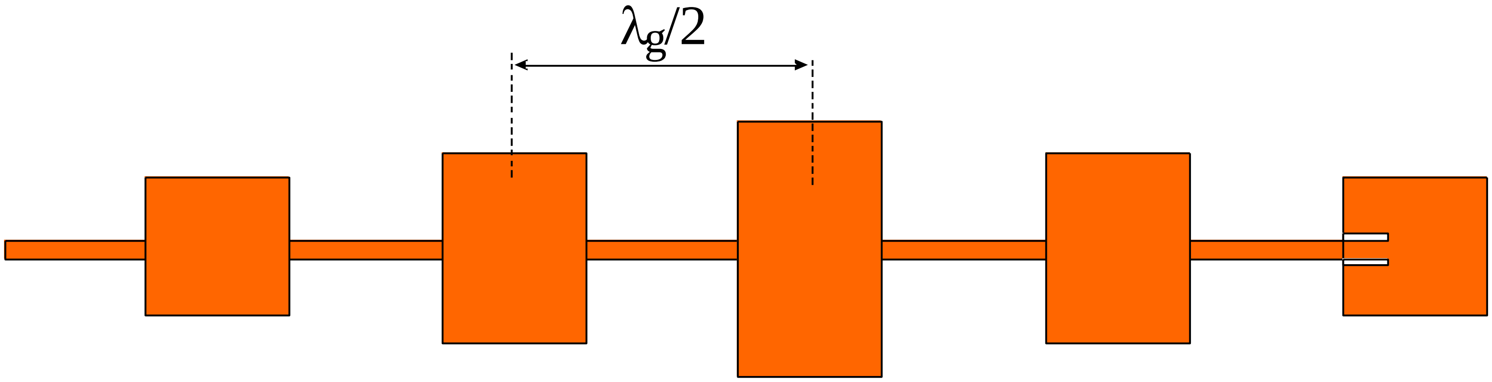
  - Pon RDA




  - Complex architecture (for phase-conjugation condition)

# SERIES-FED array

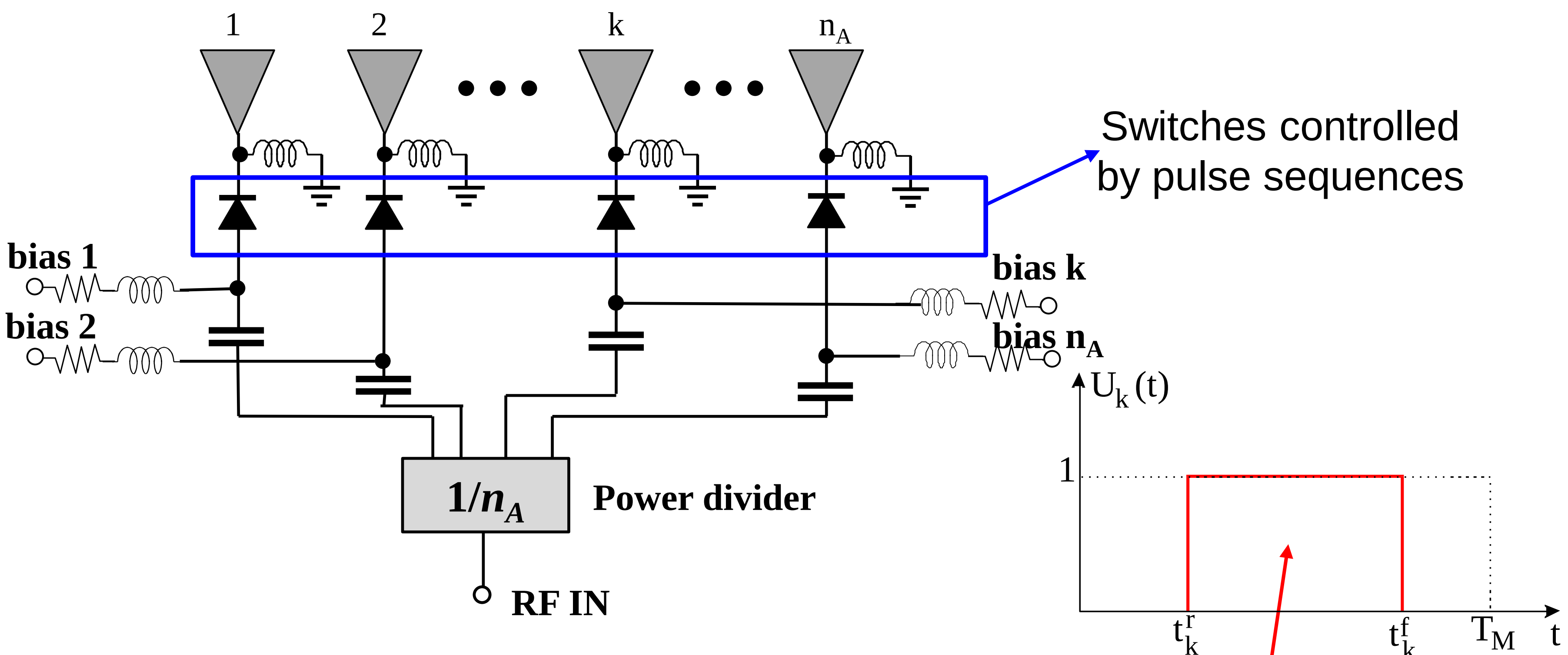
- ***SERIES-FED ARRAY***




- Complex design
- Fixed beam for a fixed frequency
- (Limited) steering capability in a frequency band

# Time-modulated arrays (TMAs)

# TMA architecture




ARRAY FACTOR OF A STANDARD LINEAR ARRAY

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

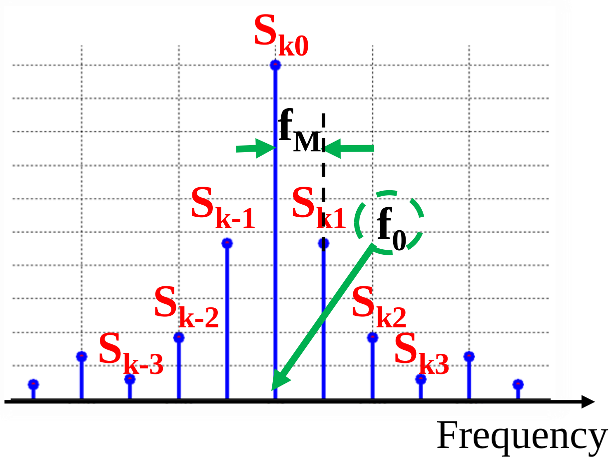
ARRAY FACTOR OF A LINEAR TMA

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

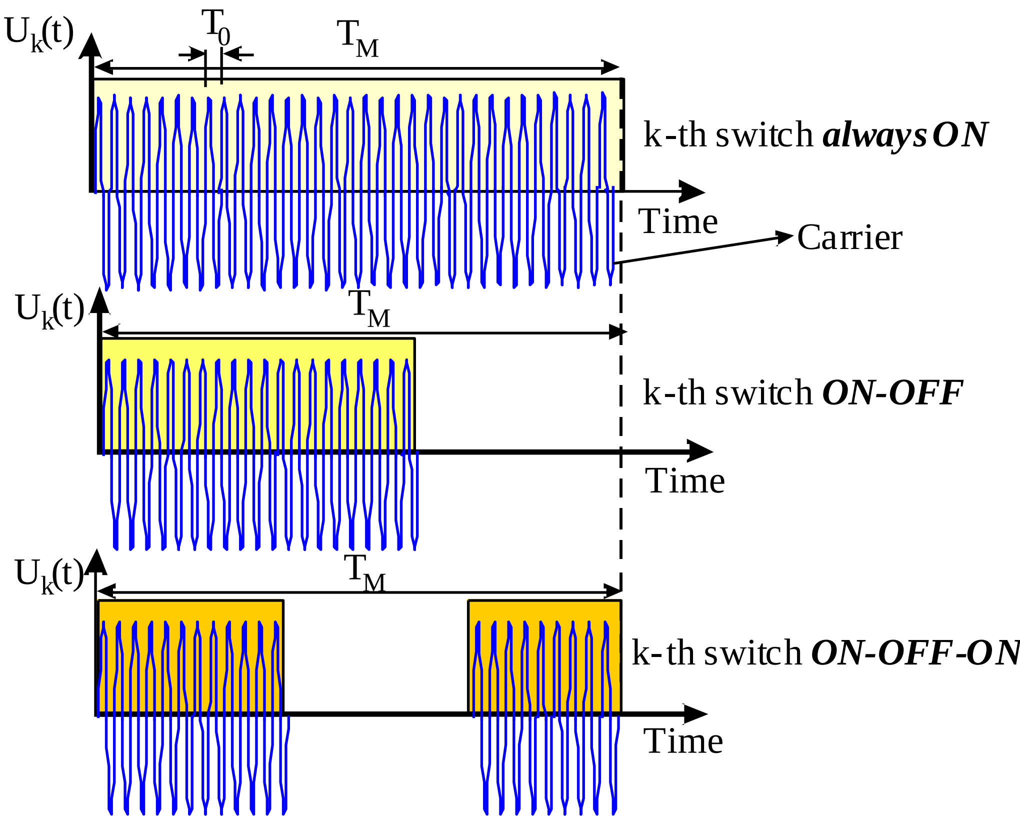
# TMA regime

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

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

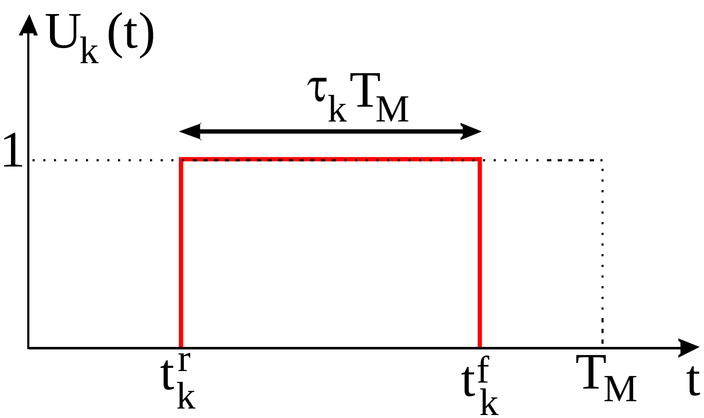



*Control pulses*



# TMA regime

- The time-dependent array factor can be Fourier-transformed:




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

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

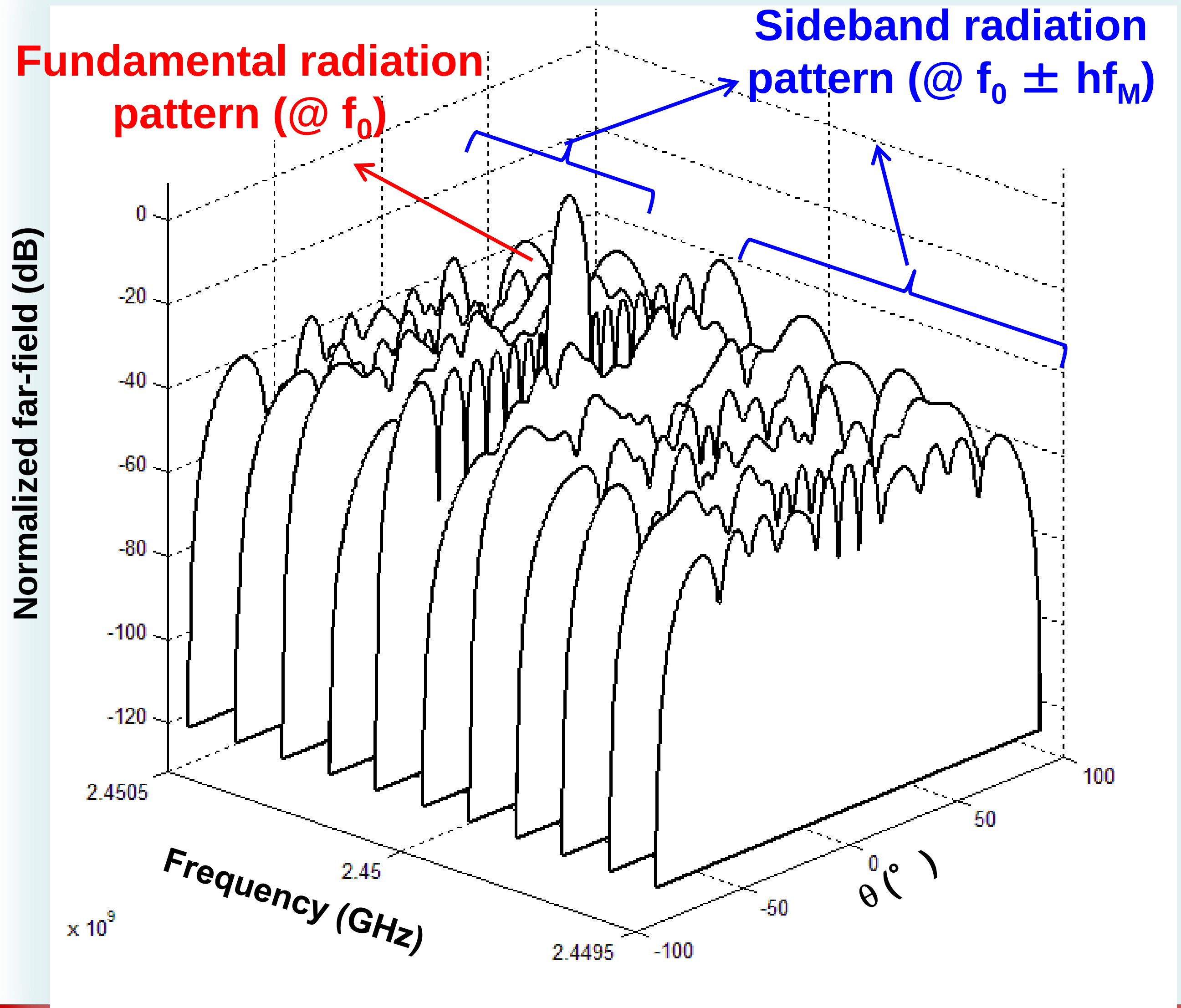
Excitation amplitudes
($\Lambda_k$=1, k=0,…n-1)

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



# TMA potentialities

- The use of ***time*** as a further design parameter allows an almost unlimited control sequence combinations in TMAs

- The ease of implementation (no phase-shifters)
- The fast software control

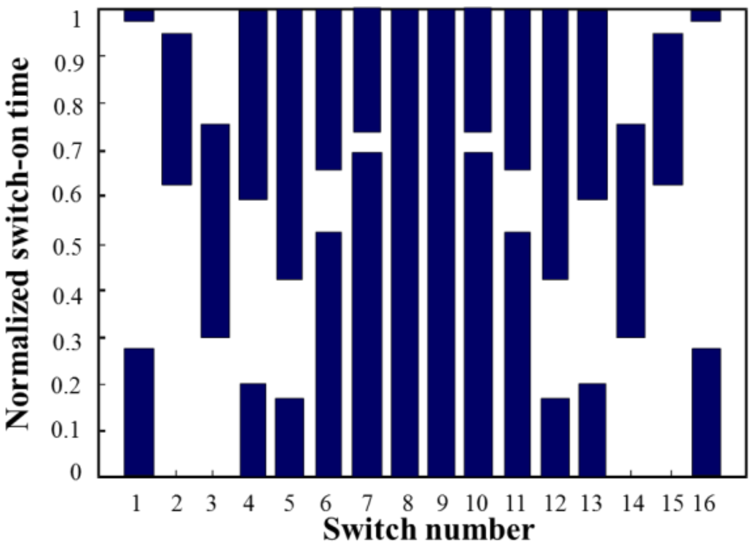
→ ***Antenna reconfiguration in real time!***

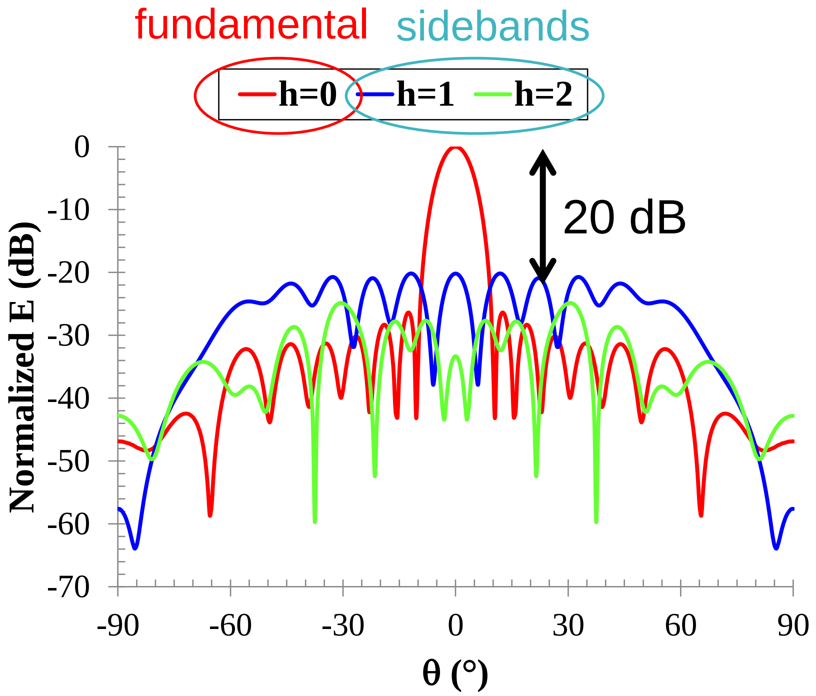
↓

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

# TMA potentialities

- ***Sideband radiation suppression***

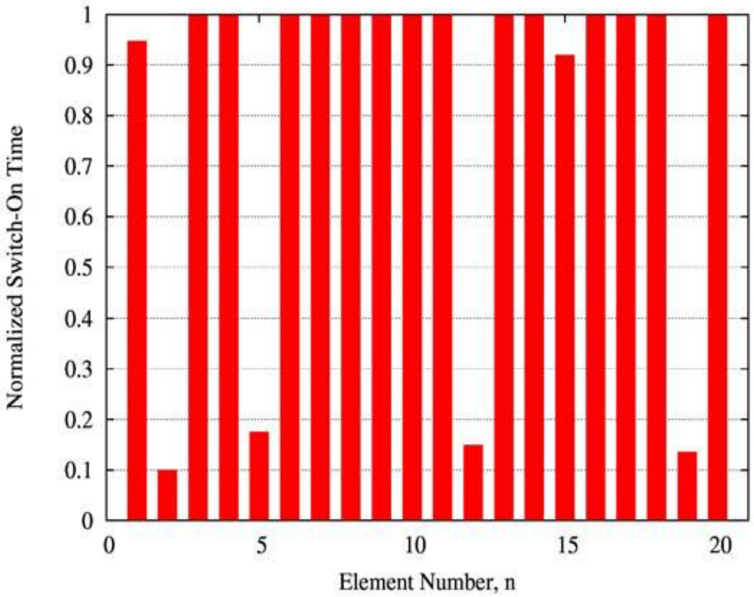


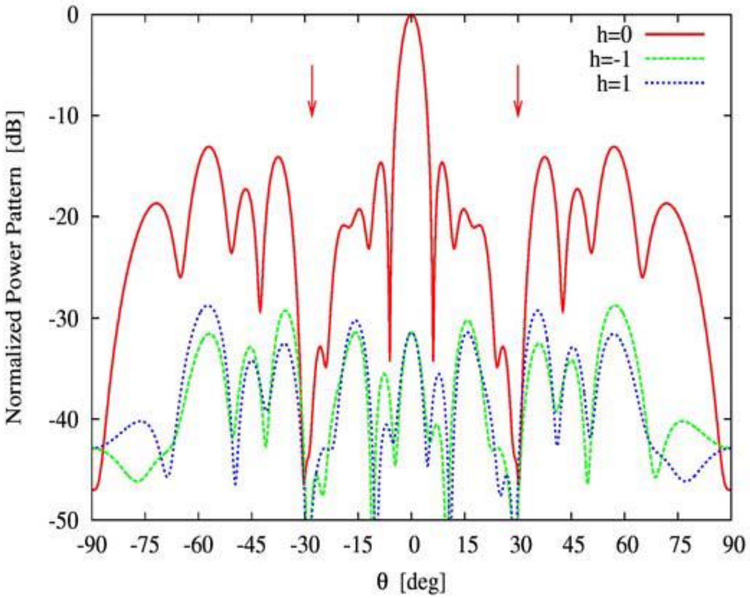




L. Poli, P. Rocca, L. Manica, A. Massa, "Pattern synthesis in time-modulated linear arrays through pulse shifting," *IET Microwaves, Ant. & Prop.*, vol. 4, no. 9, pp. 1157-1164, Sept. 2010

# TMA potentialities

- Suppress undesired interference (***Harmonic nulling***)



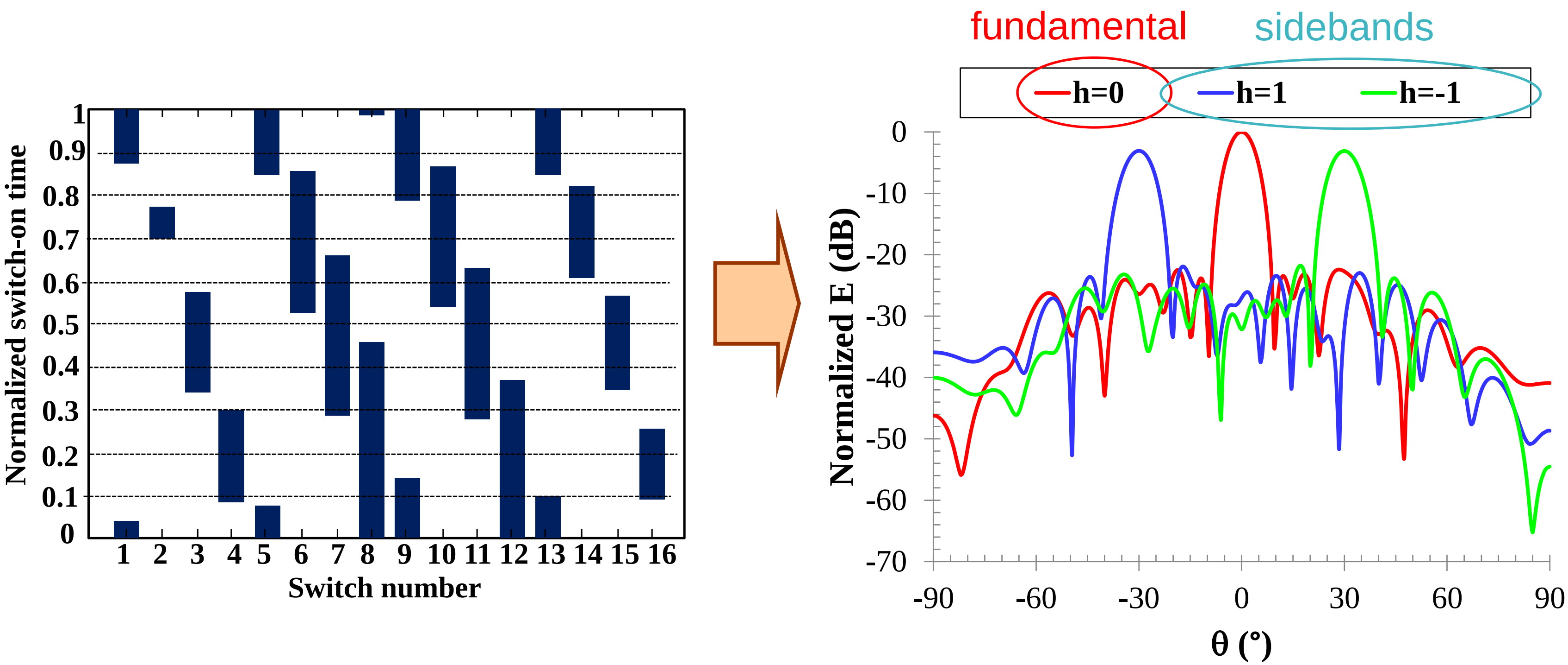




L. Poli, P. Rocca, G. Oliveri, and A. Massa, “Adaptive nulling in time-modulated linear arrays with minimum power losses,” *IET Microwaves, Antennas & Propagation*, vol. 5, no. 2, pp. 157-166, 2011

# TMA potentialities



- Exploitation of multi-channel features (***Harmonic beamforming***)



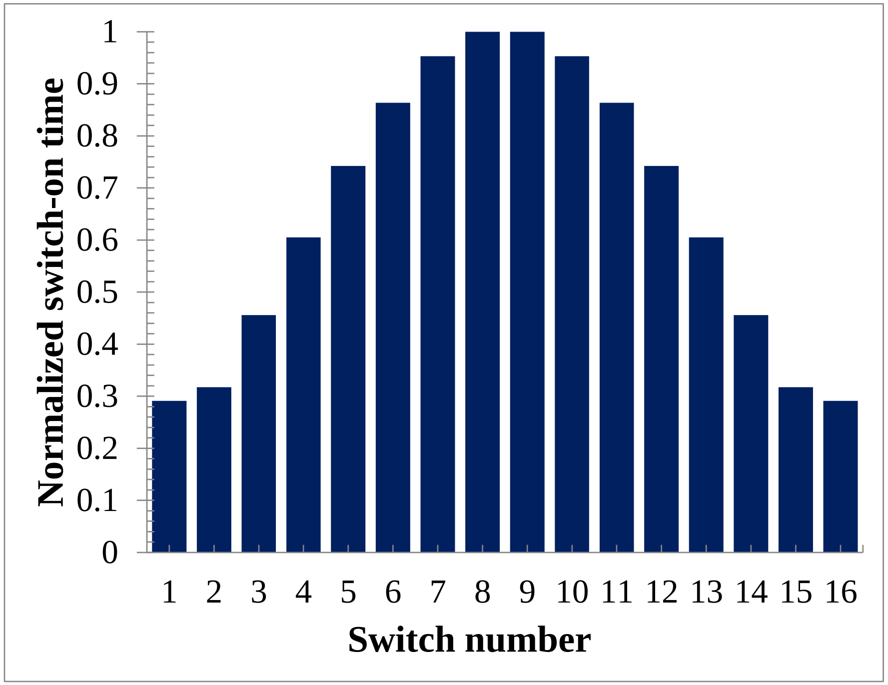

L. Poli, P. Rocca, G. Oliveri, A. Massa, “Harmonic beamforming in time-modulated linear arrays through particle swarm optimization", *IEEE Trans. Ant. & Prop.*, vol. 59, no. 7, pp. 2538-2545, July 2011

# TMA analysis/design

# TMA sequence optimization

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

***Variable Aperture Size***

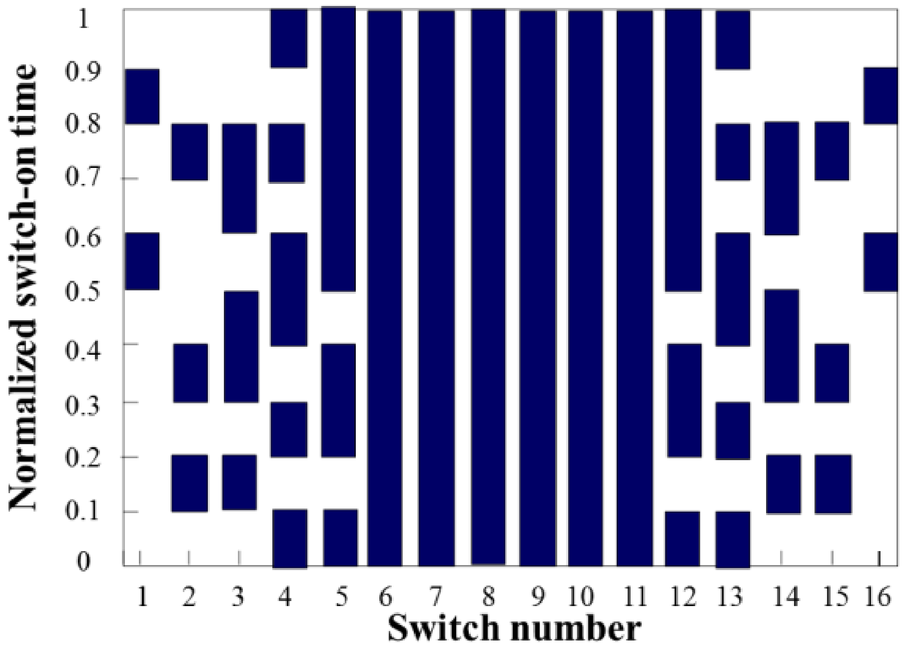



design parameter: **impulse length**

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

# TMA sequence optimization

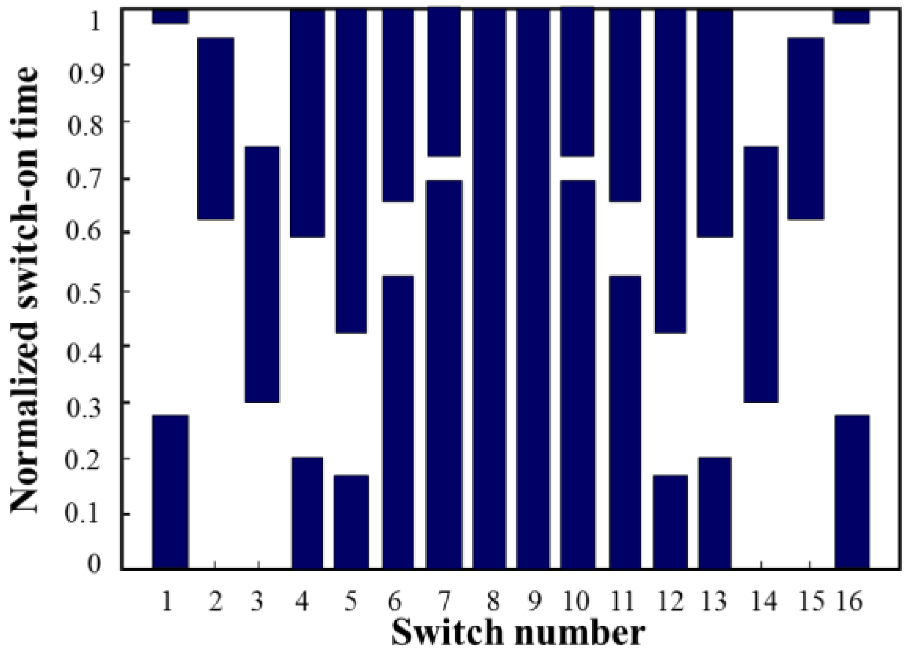
### *Binary Optimized Time Sequences*




design parameter:
**impulse sub-intervals**


S. Yang, Y. B. Gan, A. Qing, and P. K. Tan, “Design of a uniform amplitude time-modulated linear array with optimized time sequences," *IEEE Trans. on Ant. and Prop.*, vol. 53, no. 7, pp. 2337-2339, July, 2005.

## Pulse Shifting




design parameters:

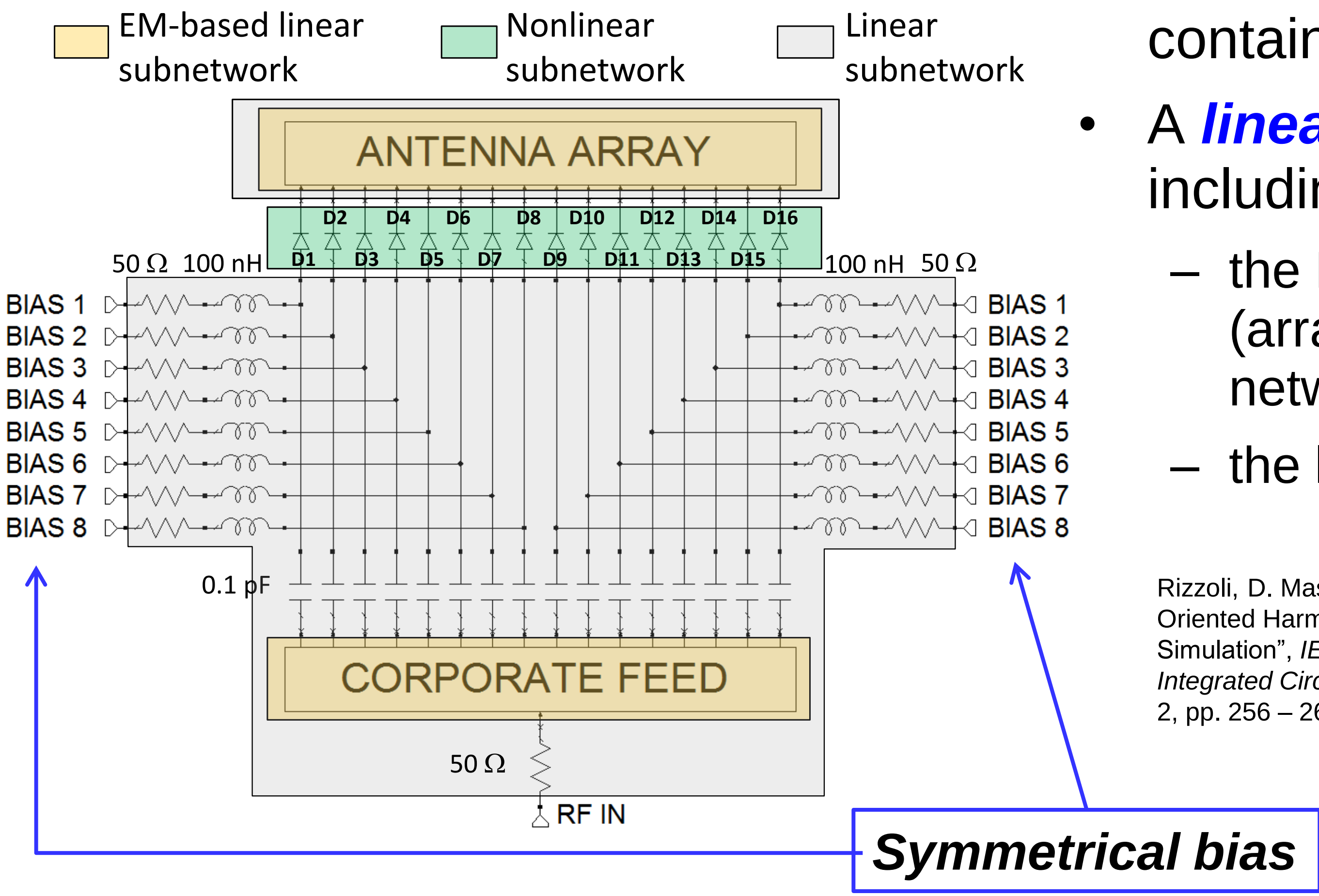
**impulse length**

**switch-on instant**

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

# NL/EM TMA co-simulation

## *Piecewise Harmonic-Balance method*




- A ***nonlinear*** subnetwork, containing 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 TMA co-simulation

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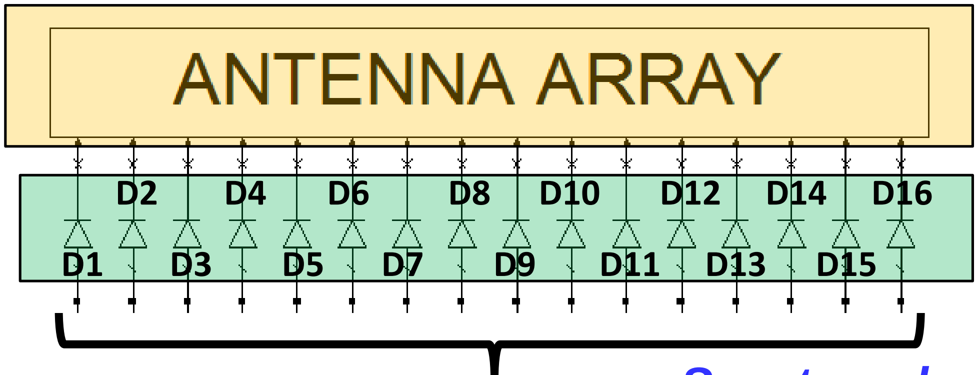
## *Far-field evaluation:* sinusoidal regime




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

***Spectrum harmonics***

***Current at i-th port***

***Antenna linearity***

$$\mathbf{E}(r,\theta,\phi;\omega_0) = \frac{\exp(-j\beta r)}{r} \bullet$$

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

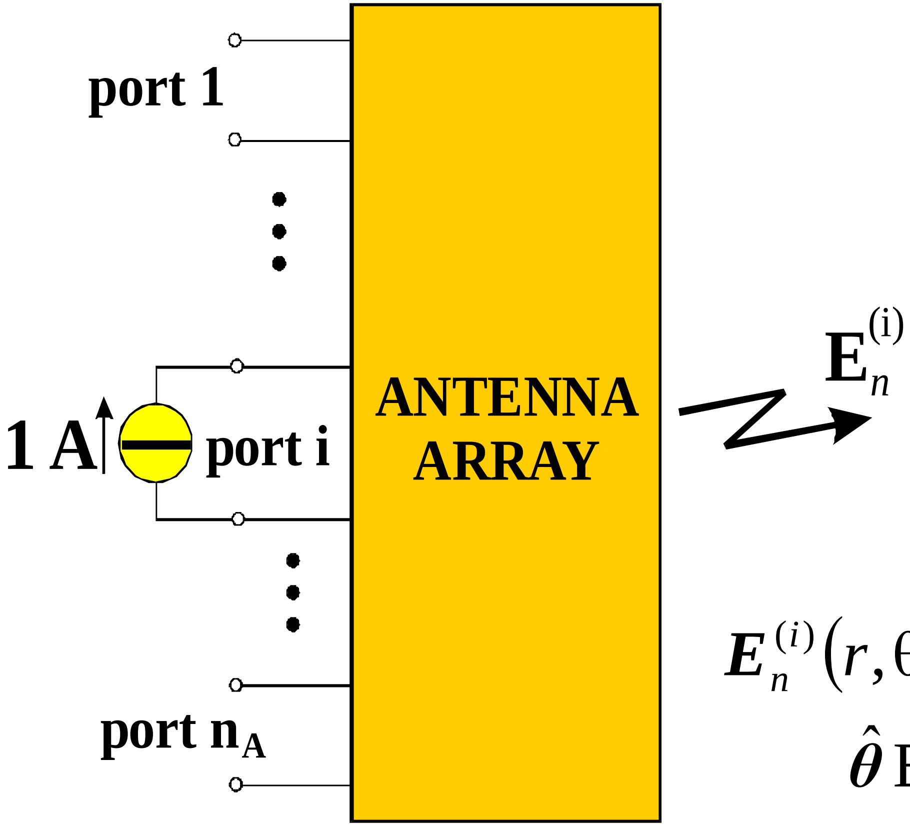
***Array ports***

***Field at the fundamental harmonic***

- $A_\theta^{(i)}$, $A_\phi^{(i)}$
  - are the scalar components of the normalized field
  - are 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




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

# NL/EM TMA co-simulation

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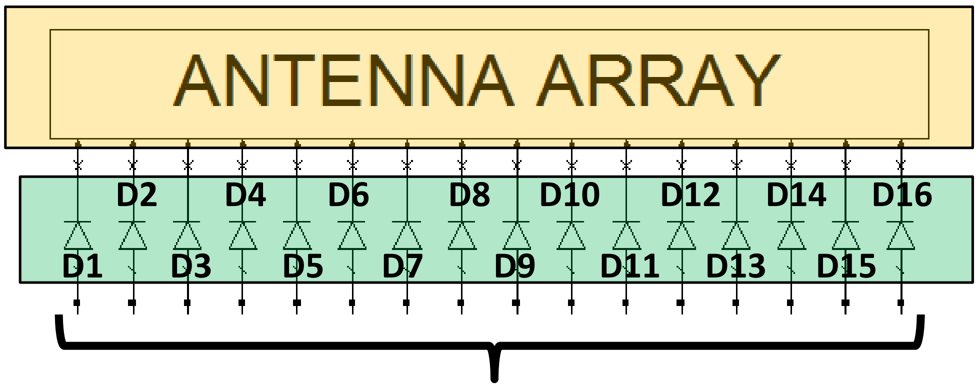
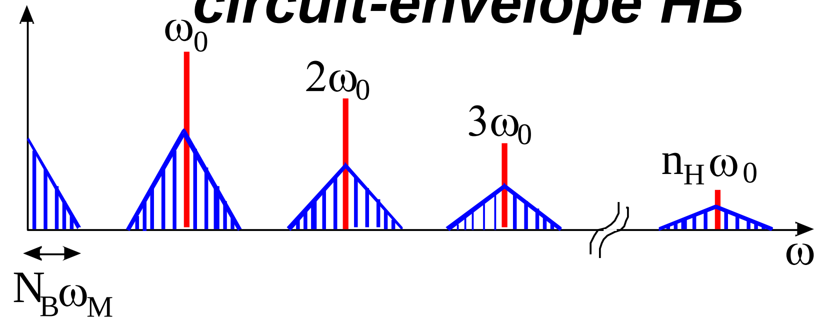
## ***Far-field evaluation:*** **modulated regime**

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




***circuit-envelope HB***




fast carrier time

slow modulation time

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

***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 TMA co-simulation

***Field envelope at the fundamental harmonic***

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

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

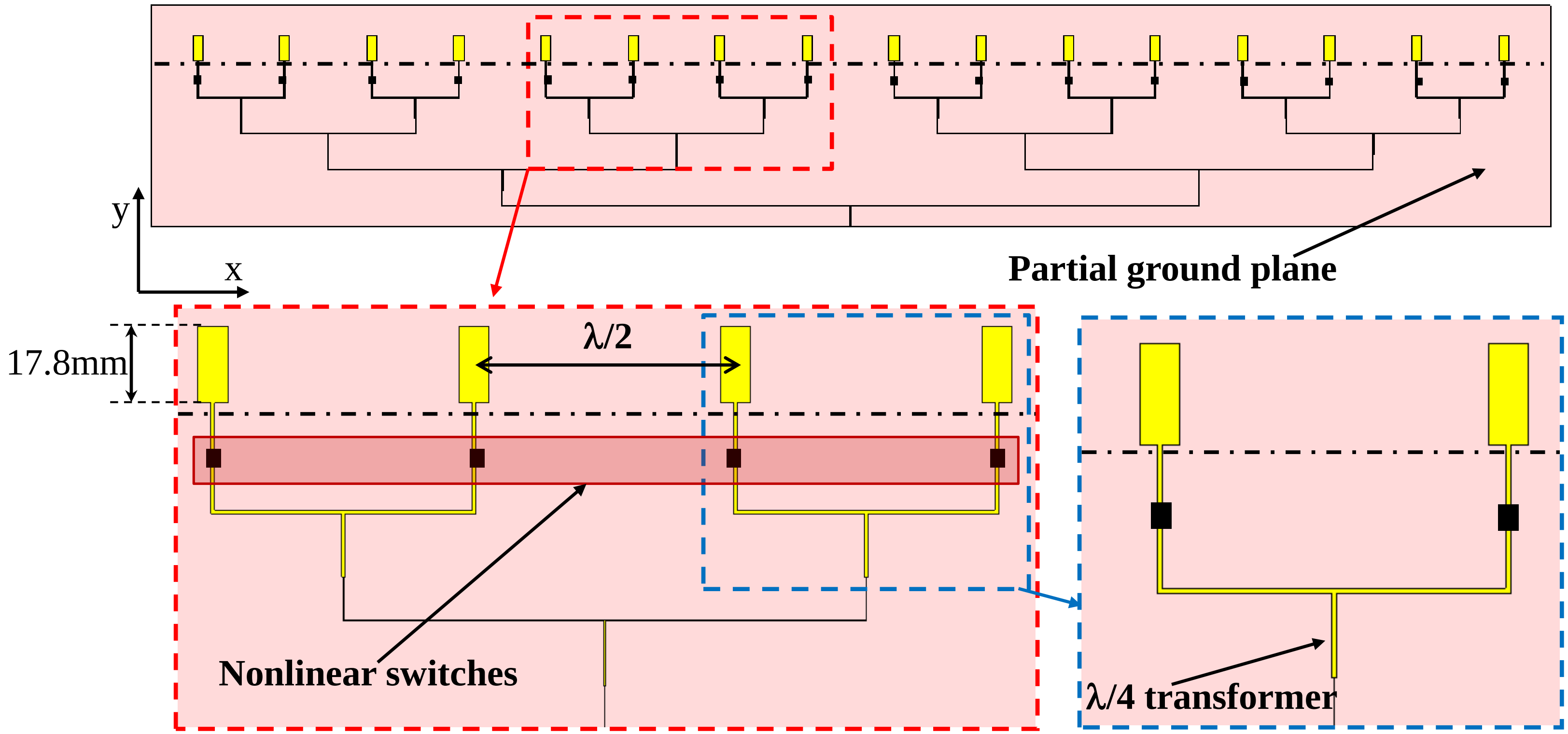
$$-\,j\,\frac{1}{r}\left[\sum_{i=1}^{n_A}\left.\frac{\partial\left\{\exp(-j\beta r)\left[\hat{\boldsymbol{\theta}}\,A_\theta^{(i)}(\theta,\phi;\omega)+\hat{\boldsymbol{\phi}}\,A_\phi^{(i)}(\theta,\phi;\omega)\right]\right\}}{\partial\omega}\right|_{\omega=\omega_0}\bullet\frac{dI_{A,1}^{(i)}(t_M)}{dt_M}\right]$$

- $A_\theta^{(i)},\ A_\phi^{(i)}$ ⇨ ***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.

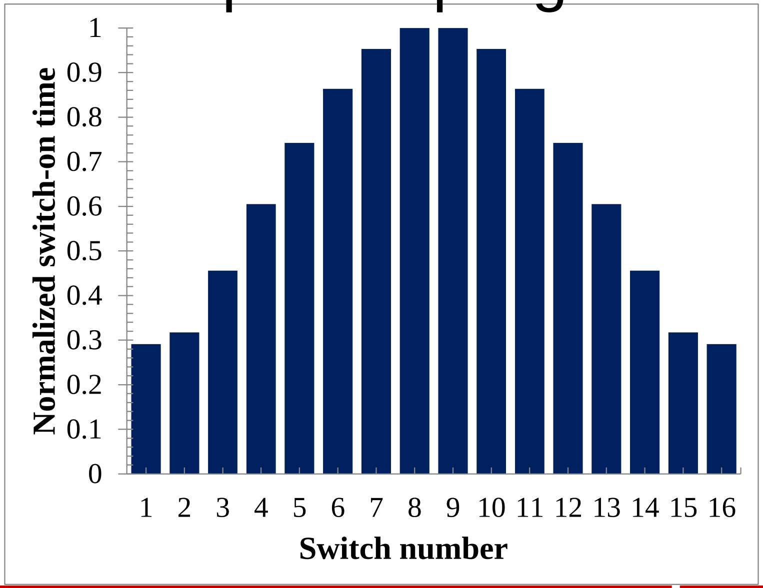
# Co-simulation results

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



# TMA under sinusoidal drive

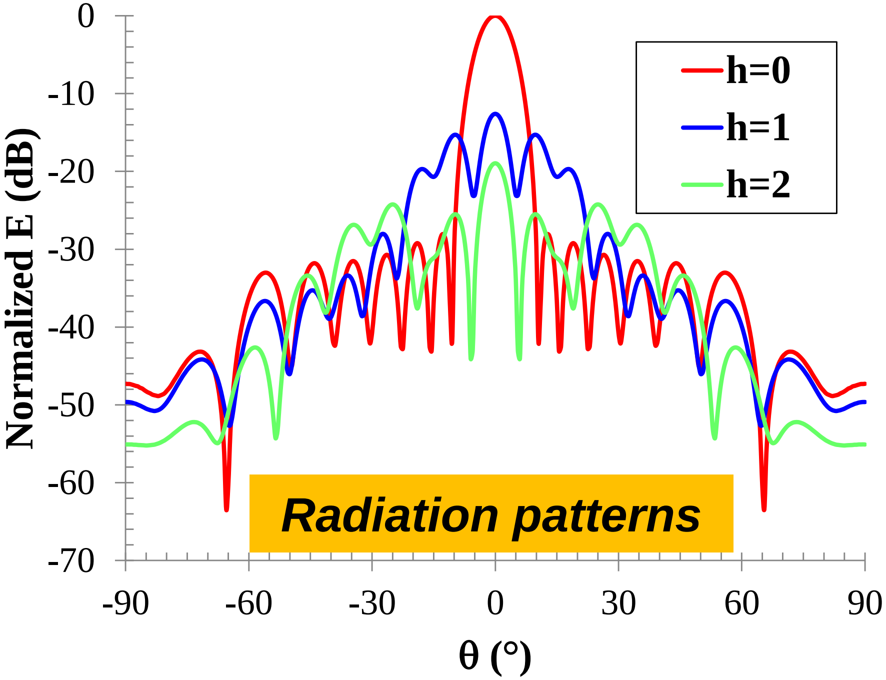
- Sinusoidal carrier $f_0$ = 2.45 GHz, $P_{RF}$ = 0dBm
- Switch modulation frequency $f_M$ = 10 kHz ($f_M << f_0$)
- Rectangular pulses with repetition period $T_M$ = 100 μs and amplitude $V_{bias}$ = 3 V are applied at the 8 bias ports (*symmetrical excitation*)
- A uniform sequence of $N_S$ = 1000 envelope sampling instants $t_n$ is chosen within the pulse repetition period
- A VAS pulse sequence reproducing the Dolph-Chebyshev pattern with side lobe level (SLL) = -30 dB is chosen



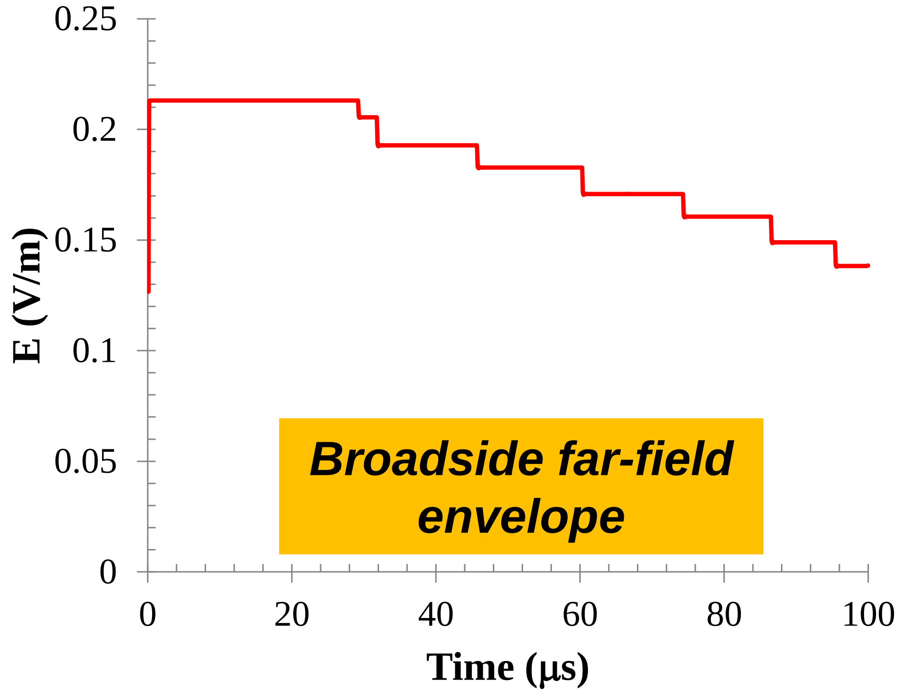
# Far-field results

$$\mathbf{E}_k(r,\theta,\phi,t_M) = \sum_{h=-N_B}^{N_B} \mathbf{E}_{kh}(r,\theta,\phi)\exp(jh\omega_M t_M)$$

$\mathbf{E}_{1h}(r,\theta,\phi)$




$\mathbf{E}_1(1m, 0°, \phi, t_M)$

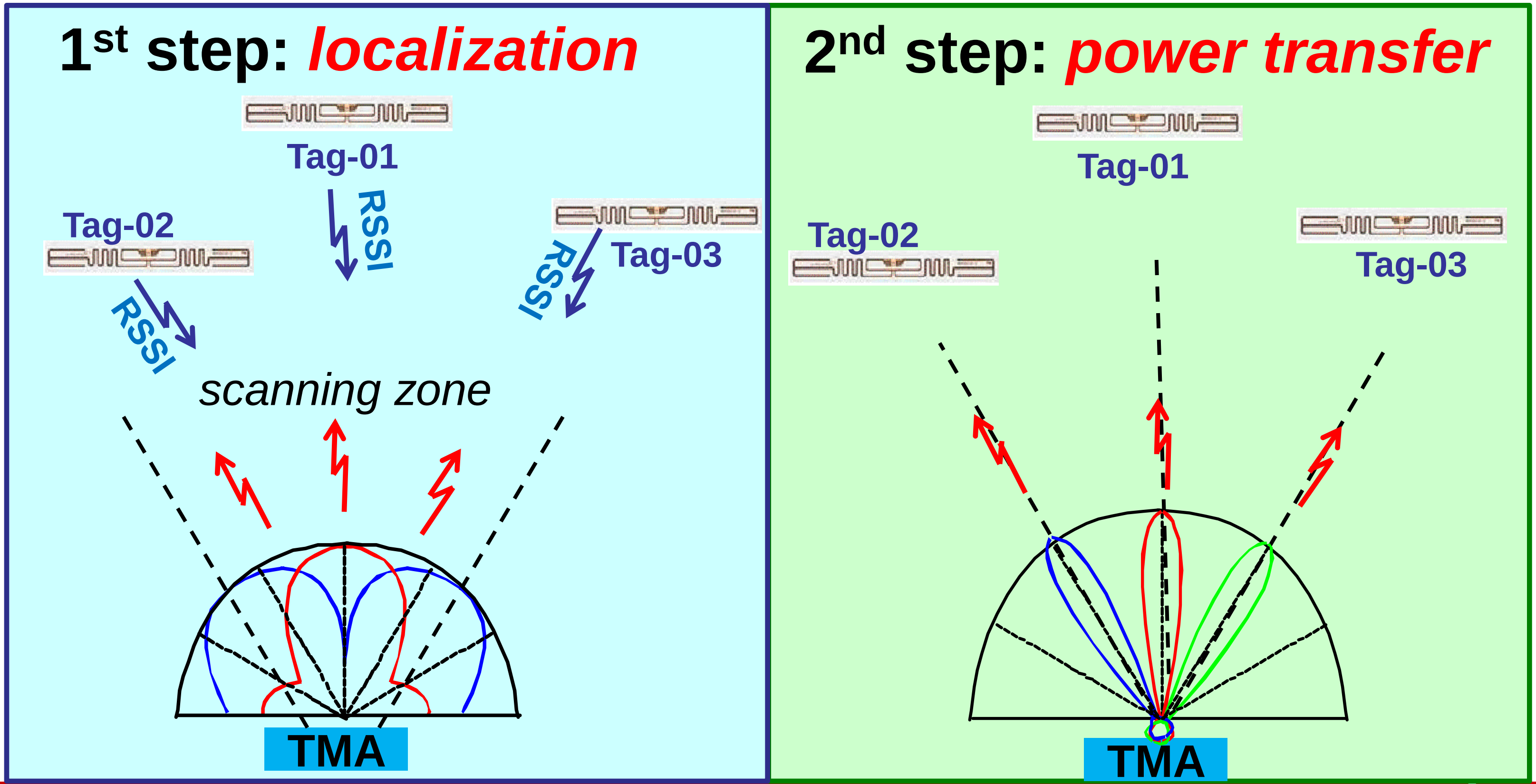



Known problem of VAS sequences: unwanted ***sideband radiation***

# Smart WPT procedure with TMA

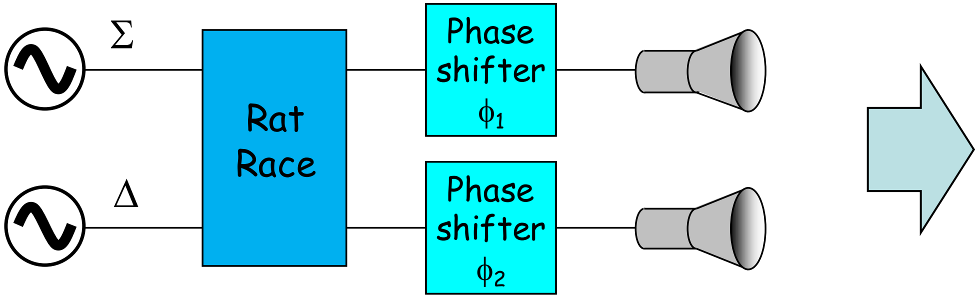
# Smart WPT with TMA

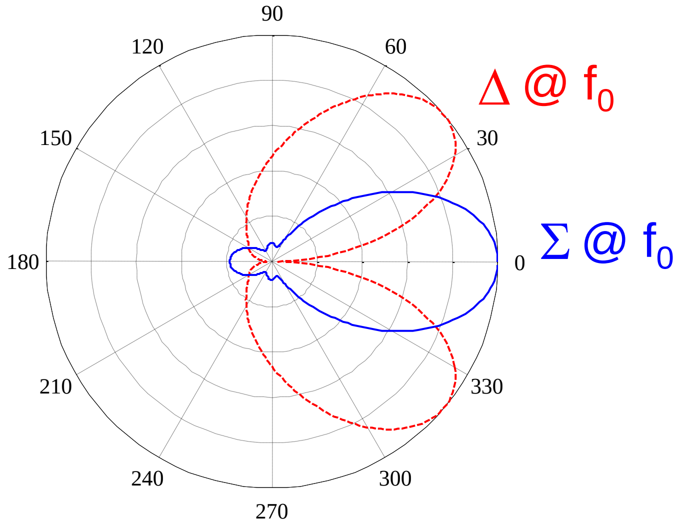
- The versatility of TMAs allows a ***smart transfer of power*** by means of a **two-step procedure**
- Scenario: room with randomly placed tagged objects



# Localization of tags

- ***Localization of tags*** with standard arrays
  - The ***Monopulse-RADAR principle*** in **standard** 2-element arrays: Σ and Δ radiation patterns are obtained from the *in-phase* (Σ) and *out-of-phase* (Δ) antennas excitation

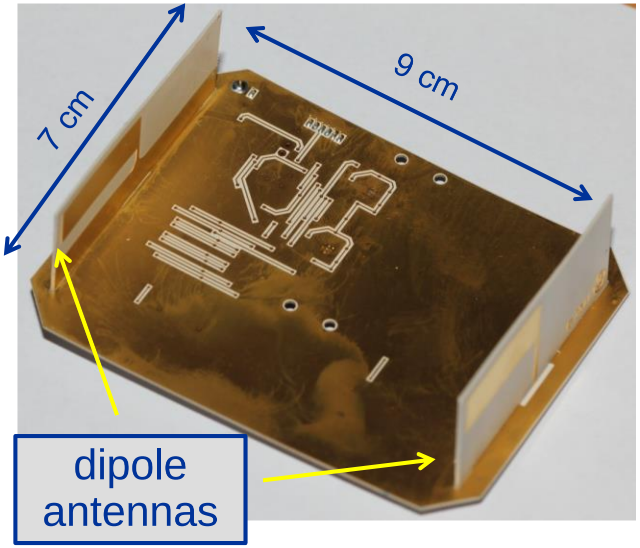


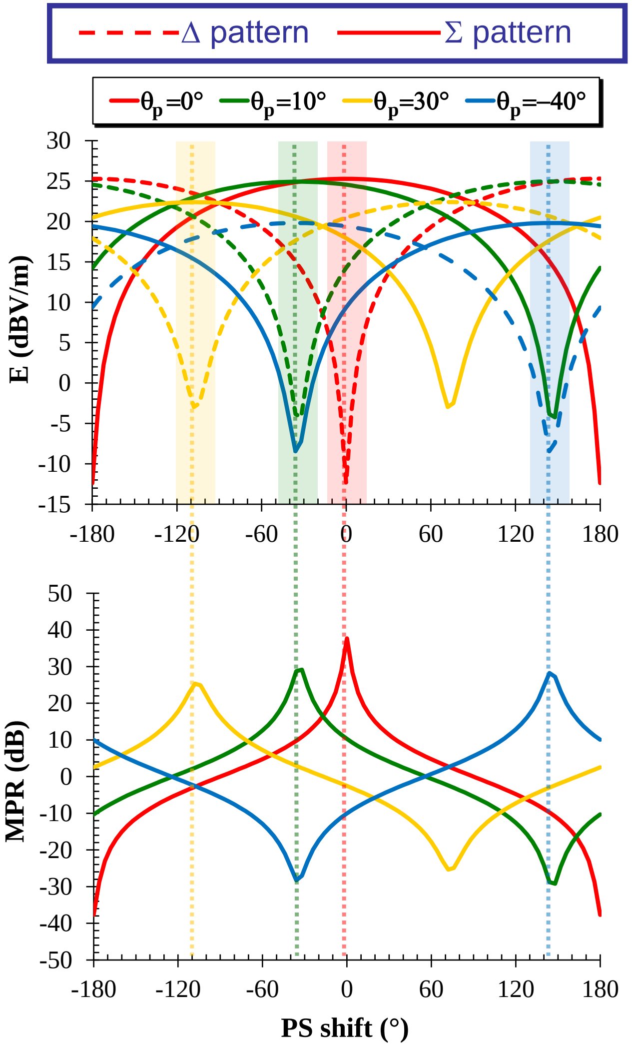




  - Additional feature of ***beam-steering*** through phase shifters at the ports

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

# Example of localization

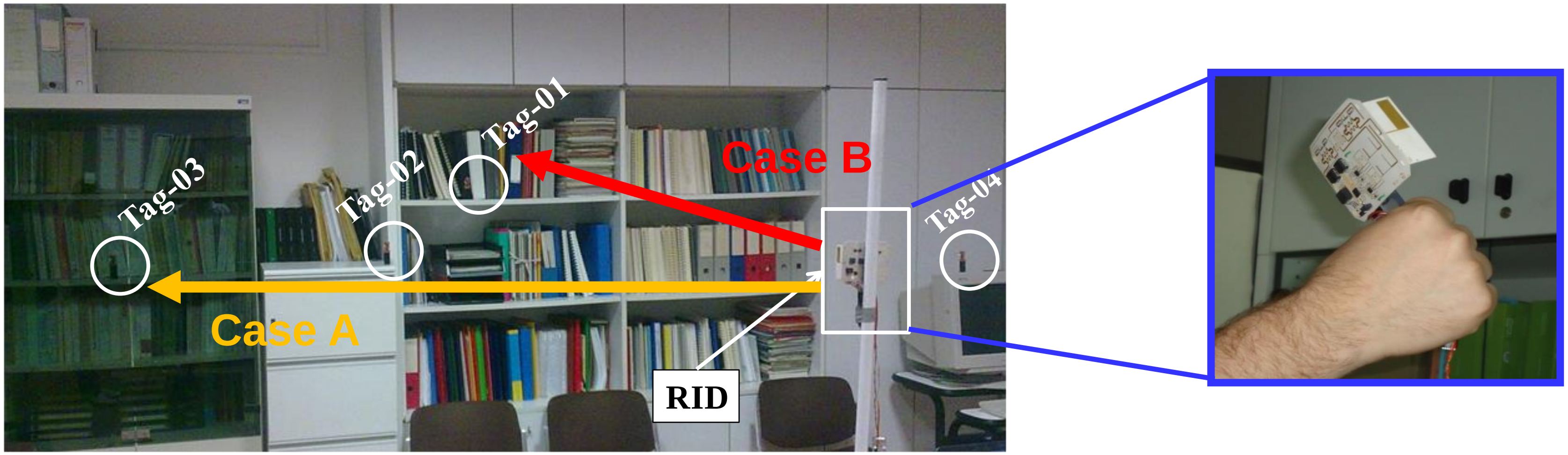


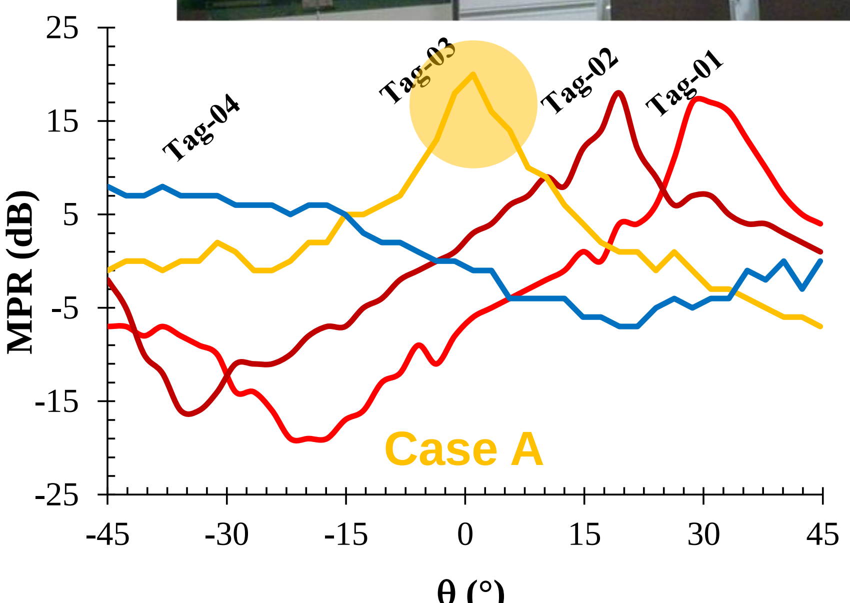



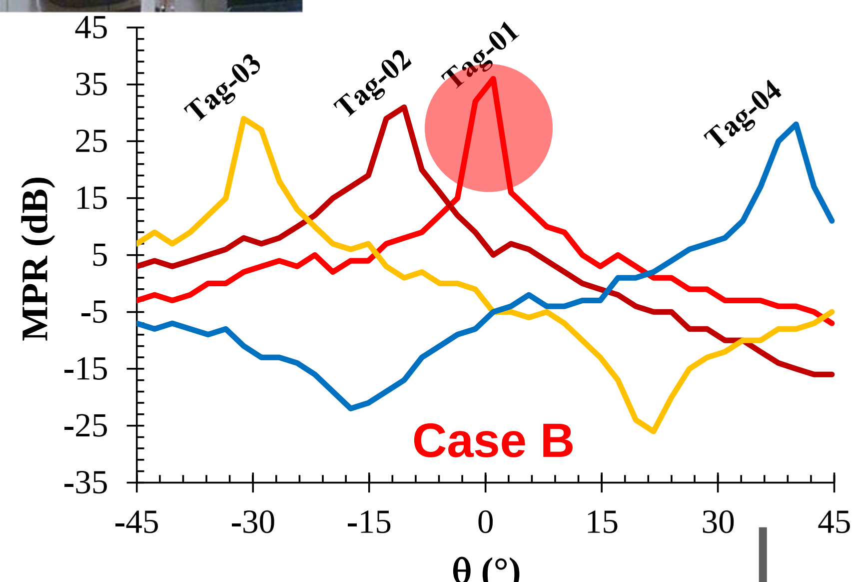

- Backscattered
  ***Maximum Power Ratio***

$$MPR(\theta) = \Sigma_{RSSI}^{dB}(\theta) - \Delta_{RSSI}^{dB}(\theta)$$

# Example of localization



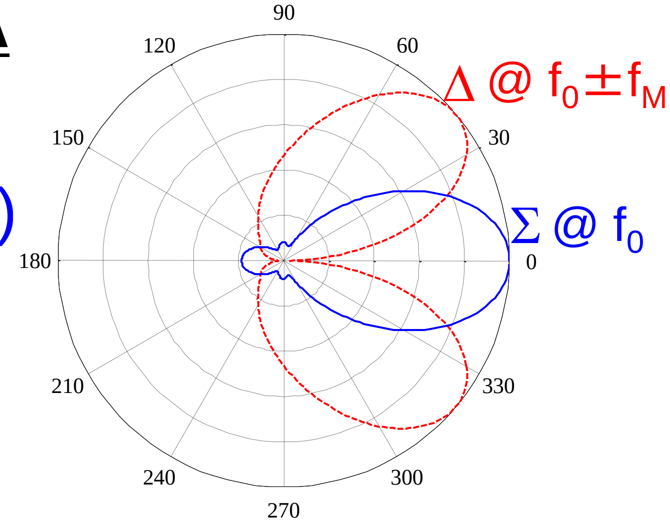



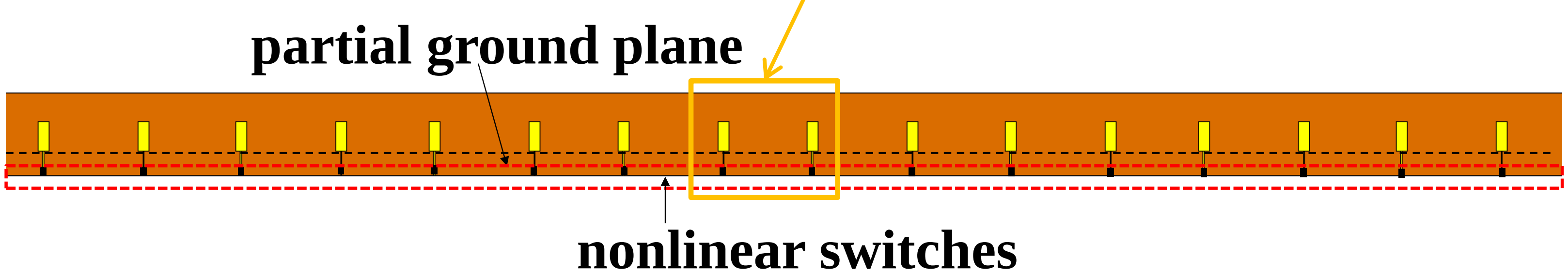
# Localization of tags

- **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



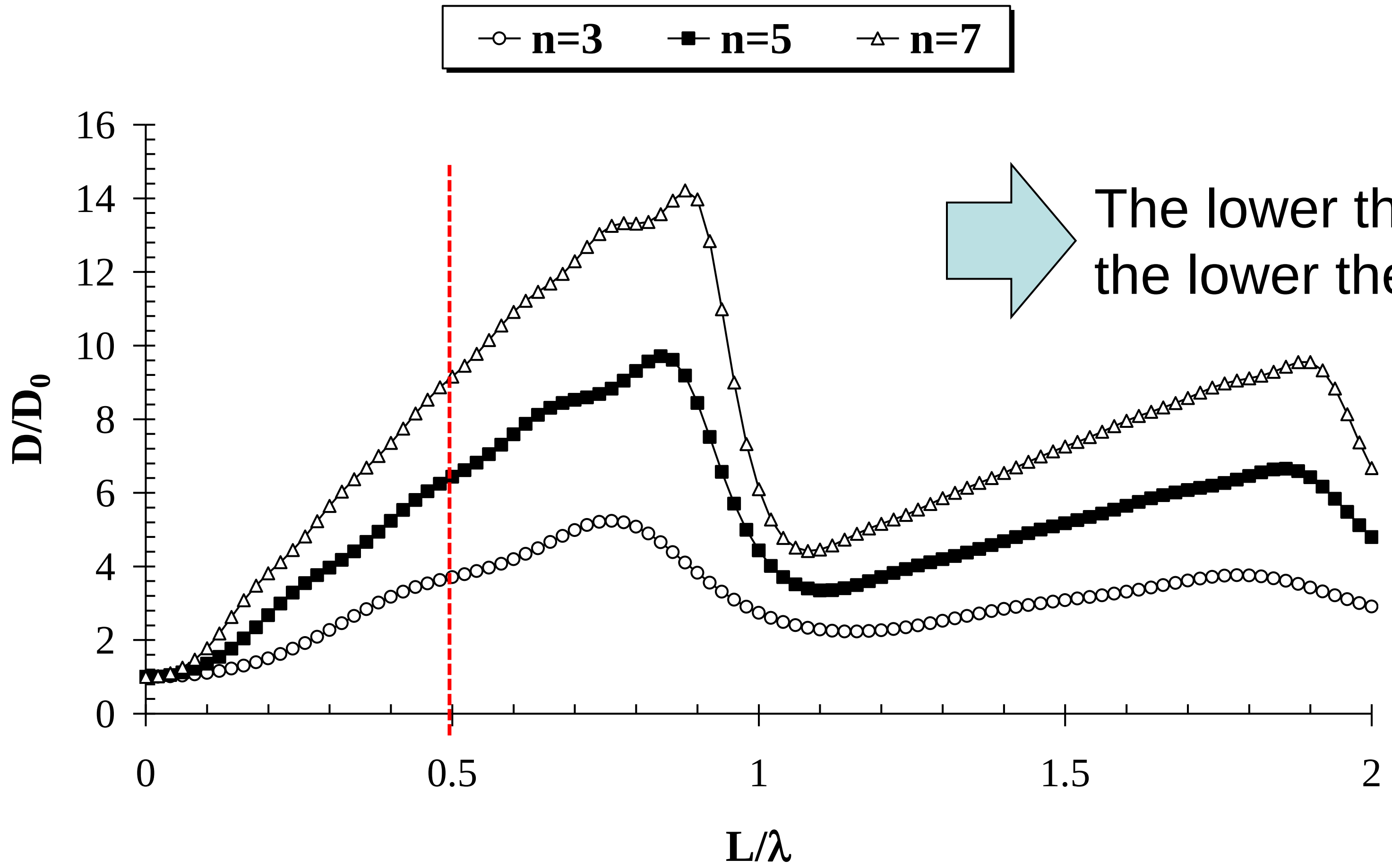

  - In our case the sole ***two-inner-element sub-array*** is operating (the other 14 peripheral switches are left open)




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

# Localization of tags

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

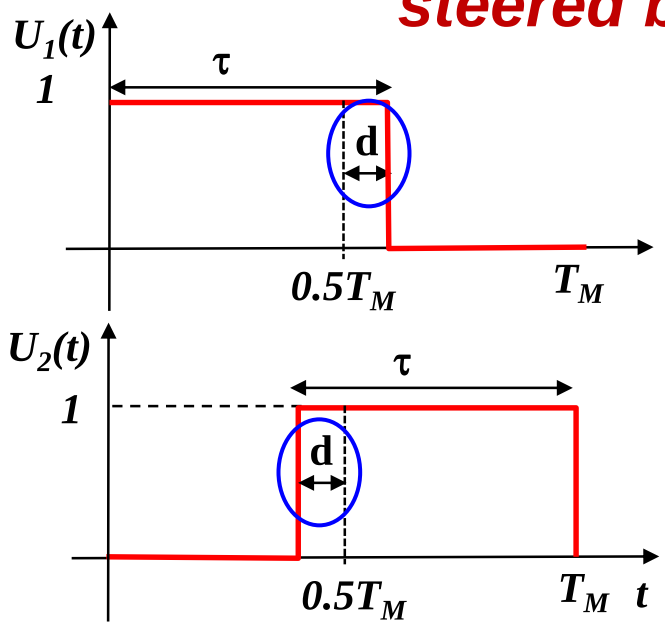



The lower the spacing L, the lower the directivity

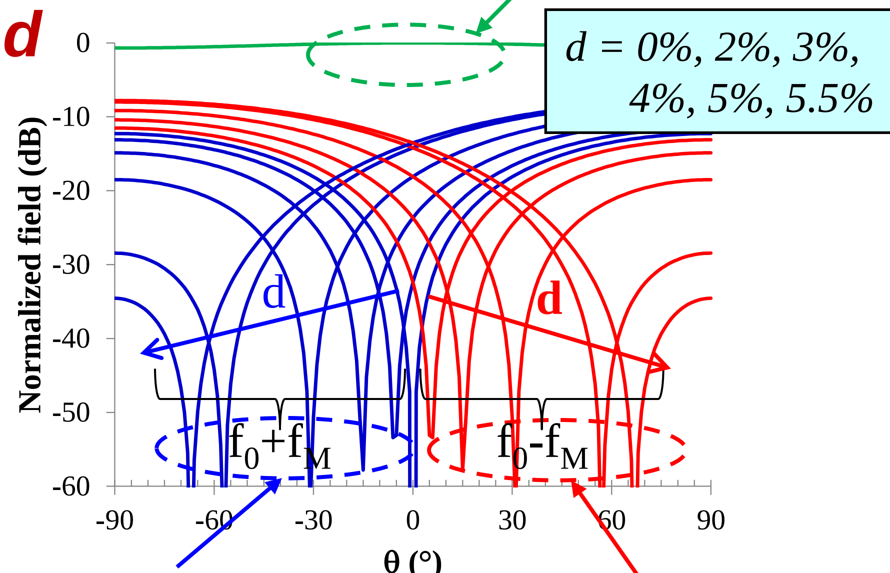
# Localization of tags

- Array of two ***isotropic*** antennas with **λ/8 spacing**, driven by tunable sequences:

***the Δ pattern can be steered by varying d***




**Sum (Σ) pattern @ $f_0$**

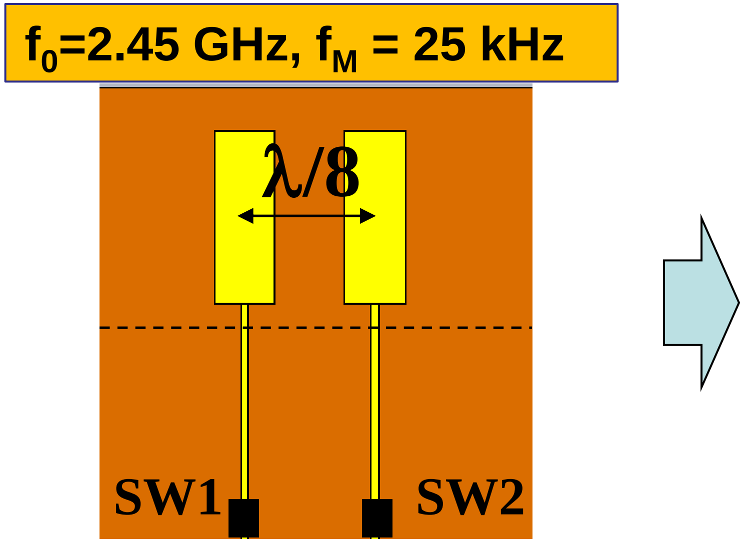



**Difference (Δ) pattern @ $f_0+f_M$**

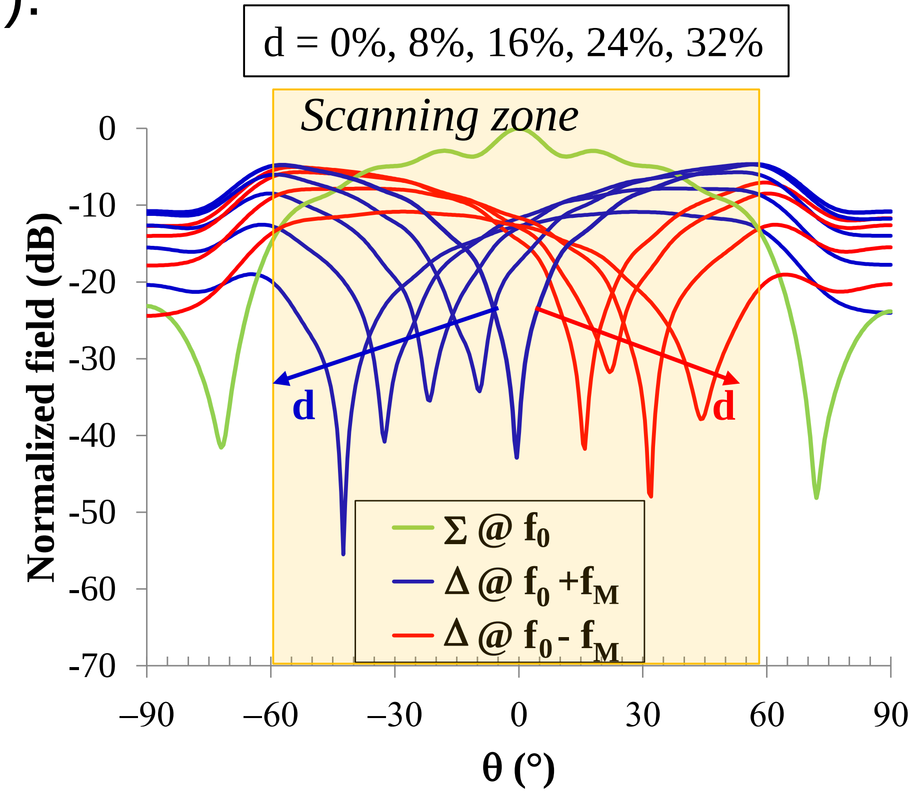
**Difference (Δ) pattern @ $f_0-f_M$**

# Localization of tags

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



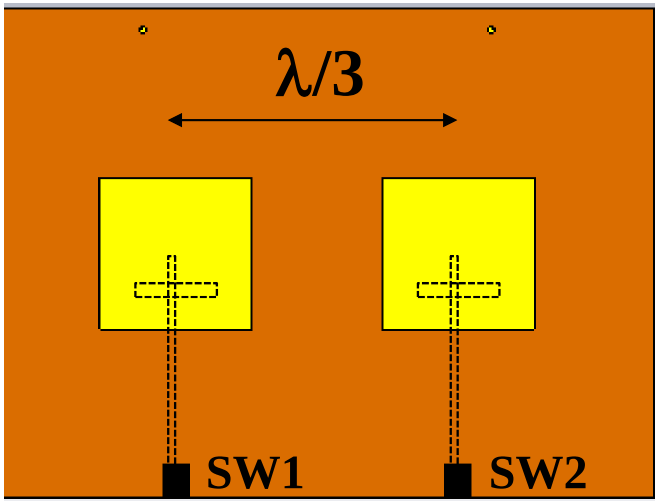

The substrate is a 0.635 mm-thick Taconic RF60A ($\varepsilon_r$ = 6.15, tanδ=0.0028)

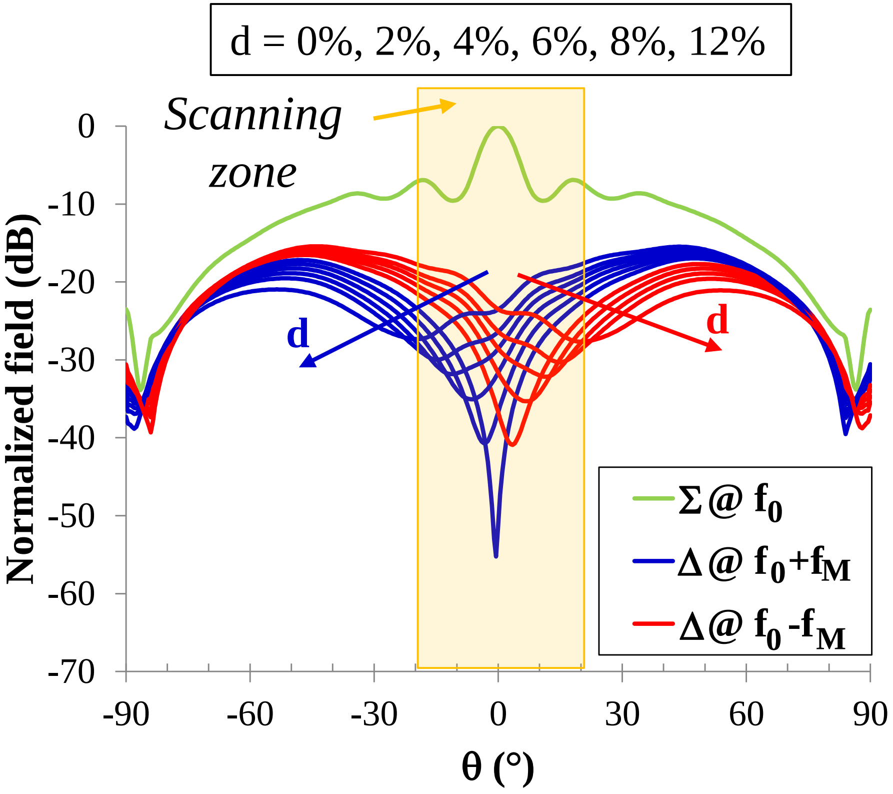



- Good scanning performance in θ∈[-60° :60° ], but with higher d values with respect to the ideal case

# Localization of tags

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



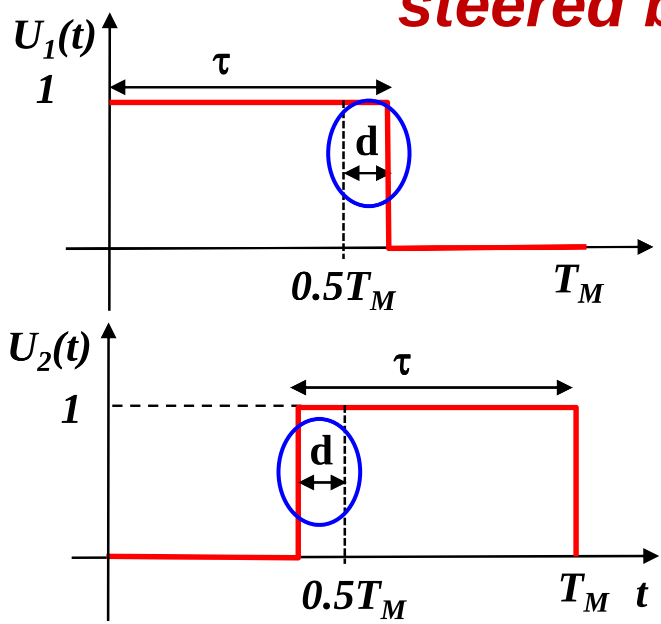




- Reduced scanning capabilities due to strong EM couplings

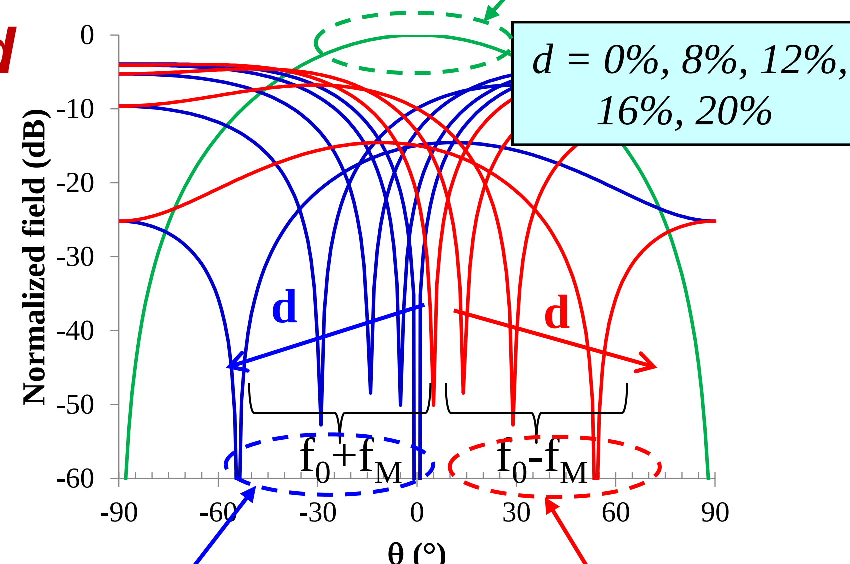
# Localization of tags

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

***the Δ pattern can be steered by varying d***




**Sum (Σ) pattern @ $f_0$**

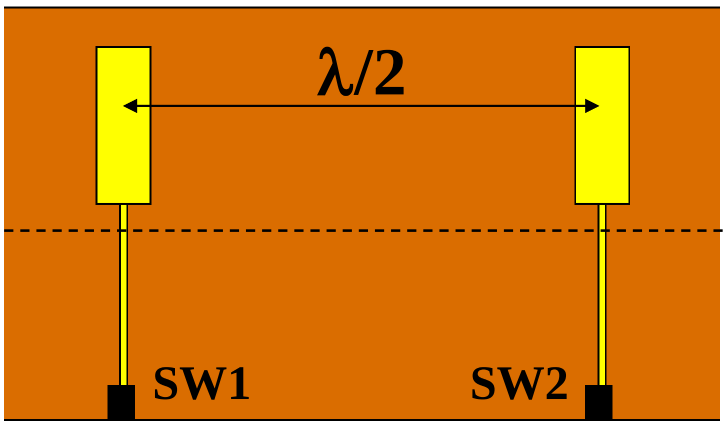


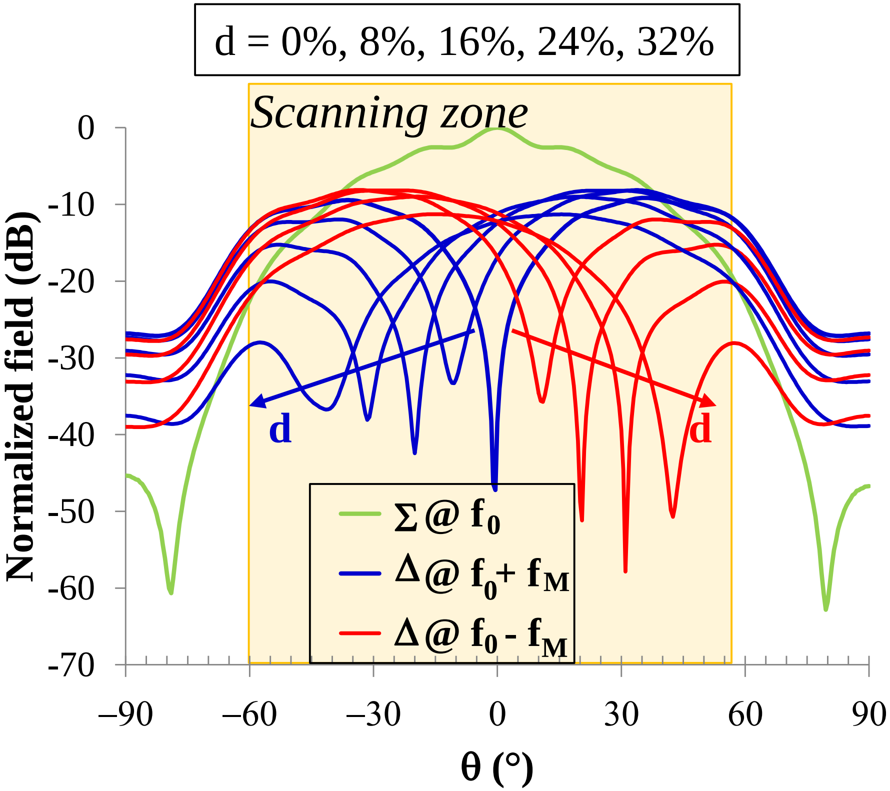

**Difference (Δ) pattern @ $f_0+f_M$**

**Difference (Δ) pattern @ $f_0-f_M$**

# Localization of tags

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

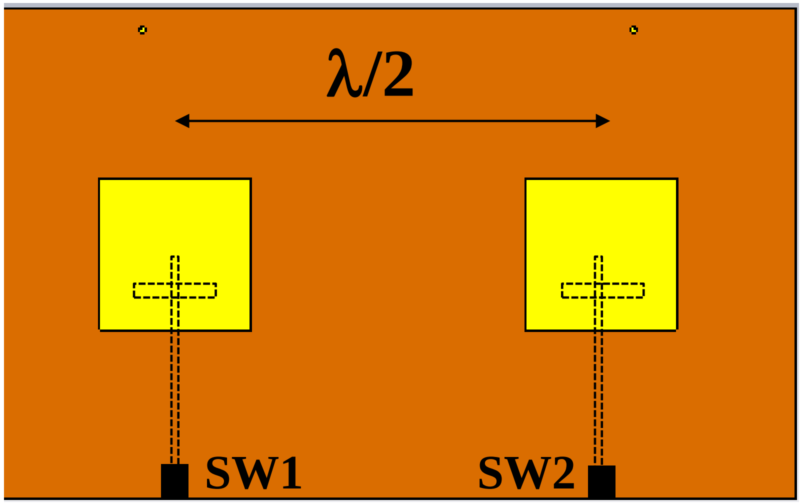


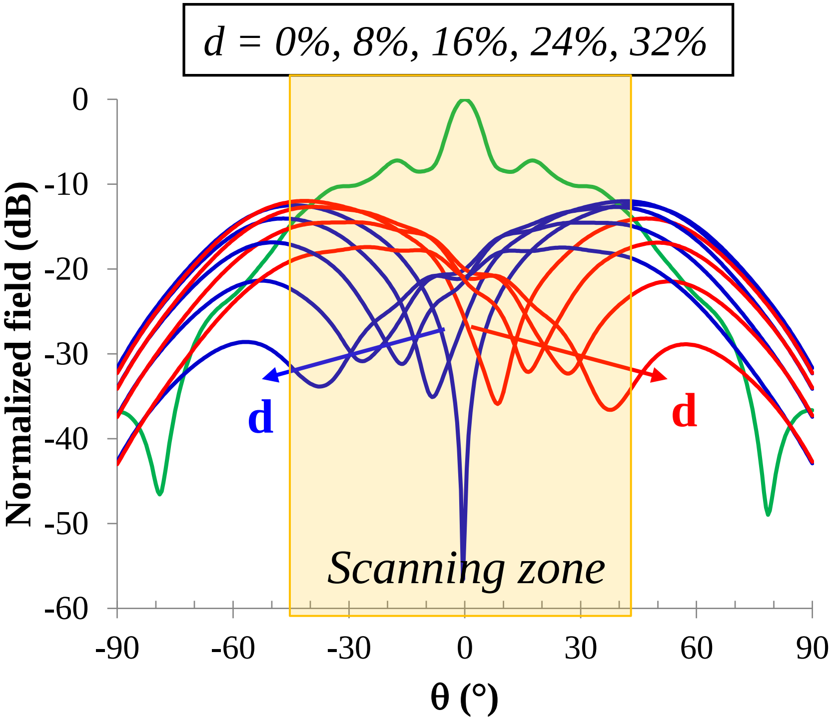




- Good scanning performance in θ∈[-60° :60° ]

# Localization of tags

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




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

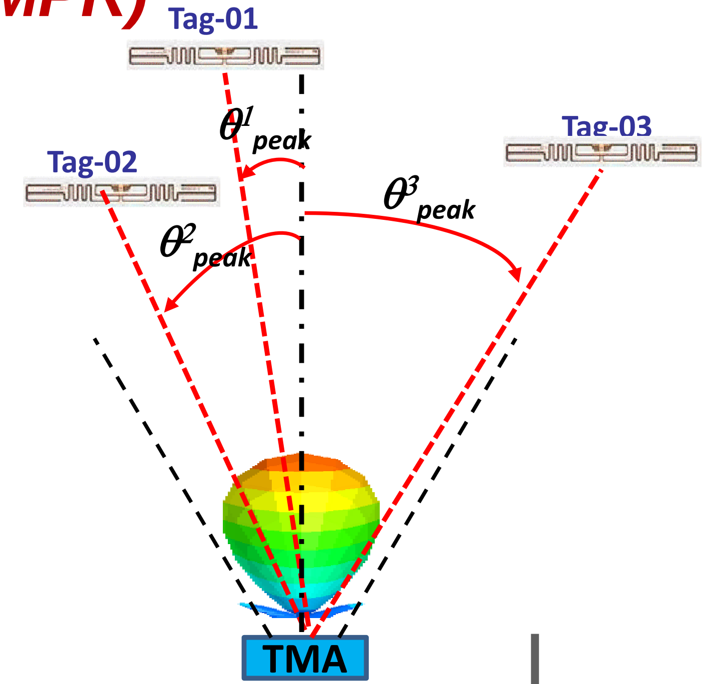
# Localization of tags

- The sharp nulls of the steered Δ 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)***

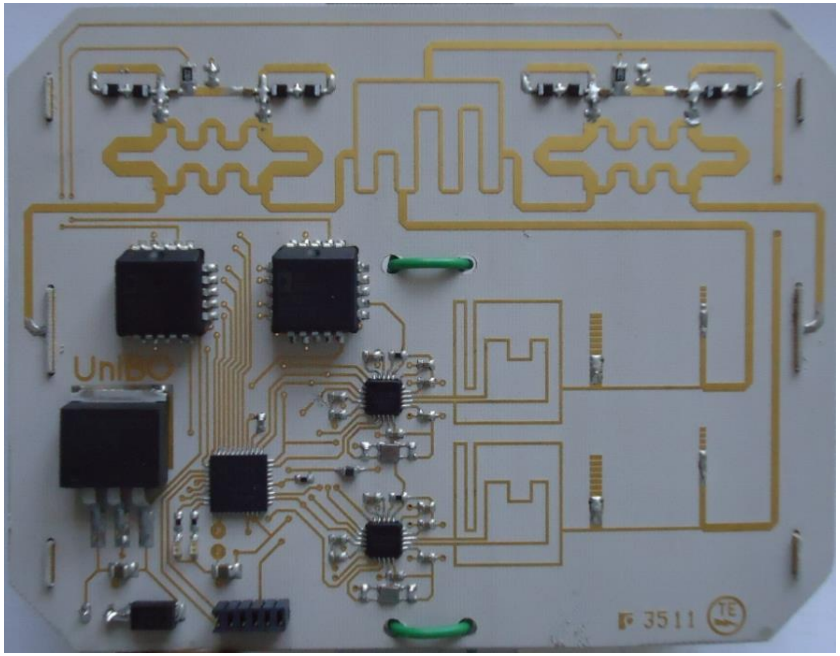
$$MPR(\theta) = \Sigma_{RSSI}^{dB}(\theta) - \Delta_{RSSI}^{dB}(\theta)$$

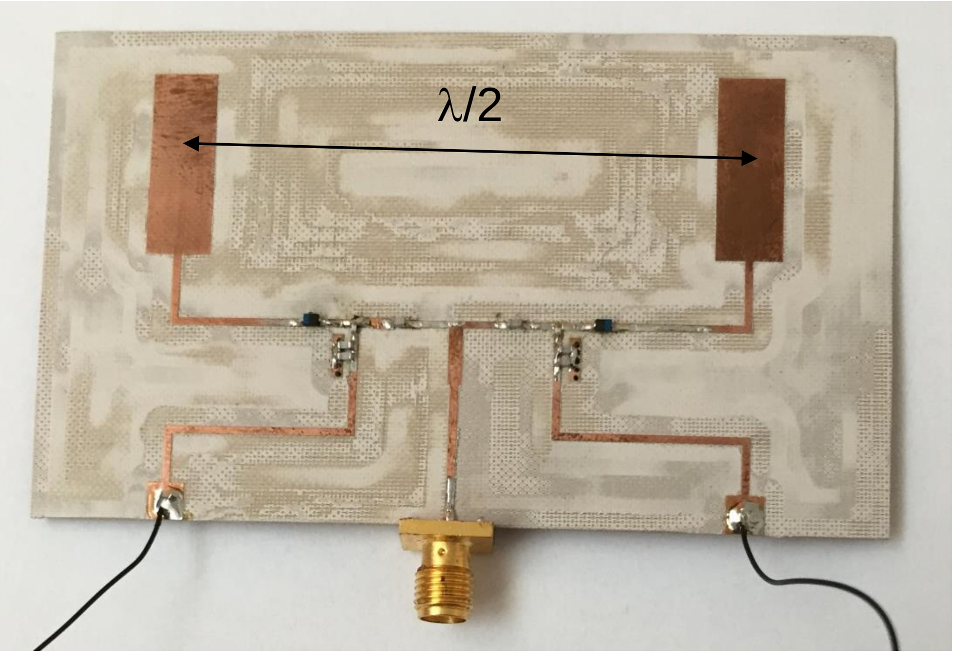
$\theta^{i}_{peak}$ ; $i=1,\ldots, N_{tag}$

***List of recordered tags position***



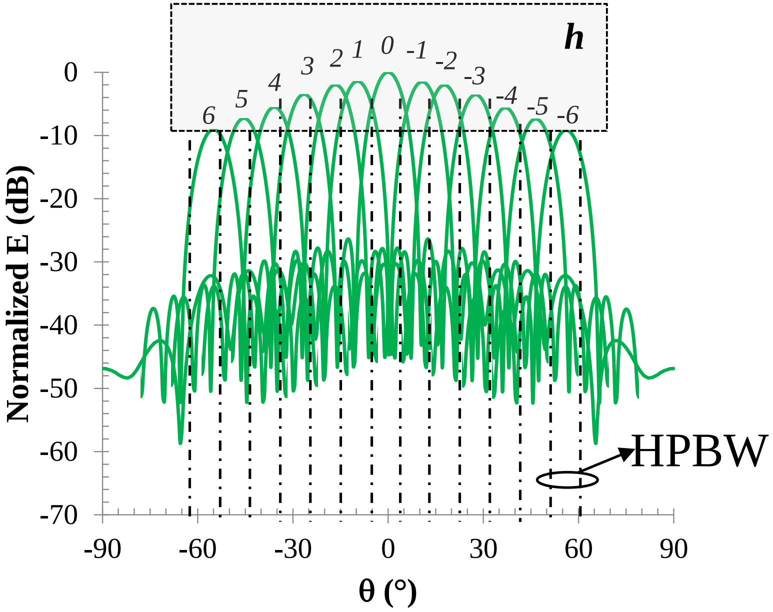
# Arrays for localization: a comparison





# Transfer of power to tags

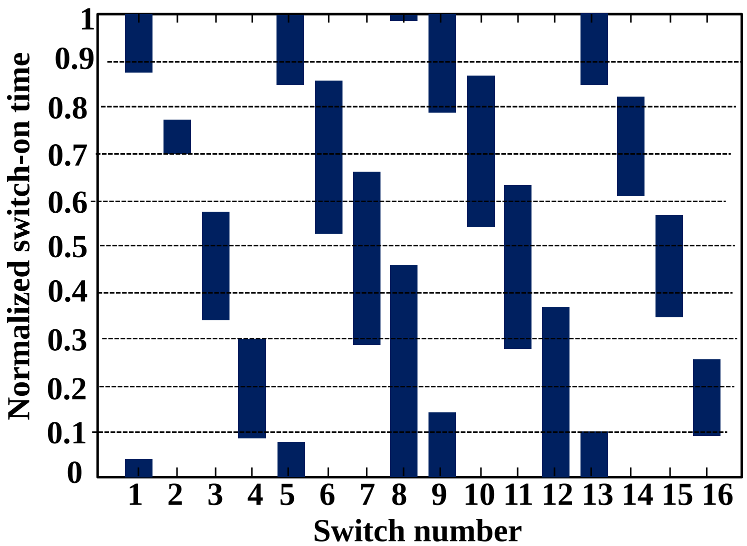
- **2° step:** ***Transfer of power to tags***
  - ***The whole 16-element array*** is driven by proper ***pre-loaded control sequences*** involving all the switches
  - Possible decision rule:
    - split the scanning region ($\theta \in [-60° \div 60°]$) into sectors of amplitude equal to the half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

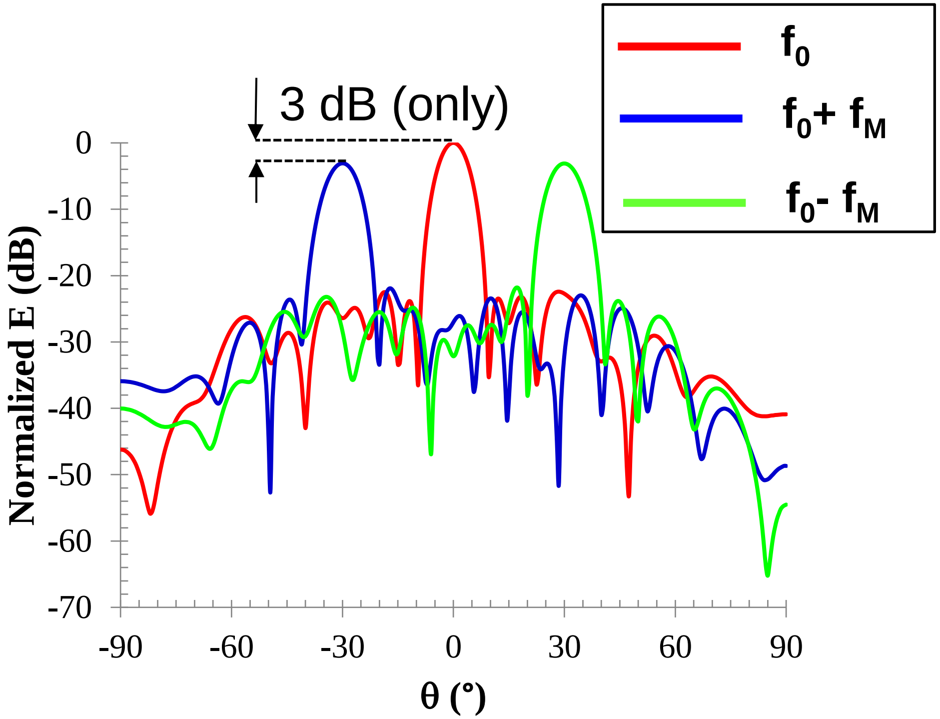


# Transfer of power to tags

- In case of $\theta_{peak}$ falling into the sectors centered around $\theta_{HPBW}$ = -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

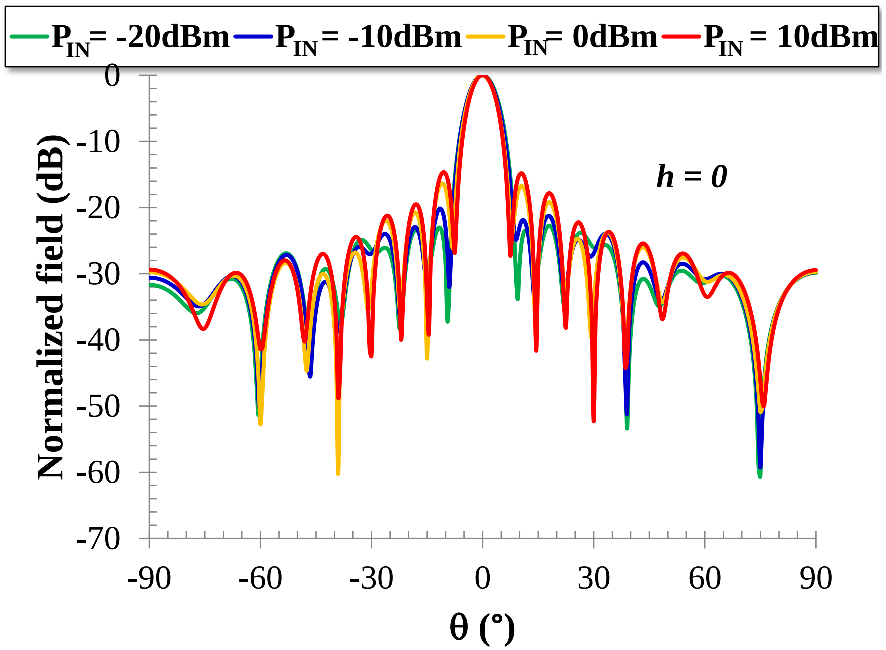


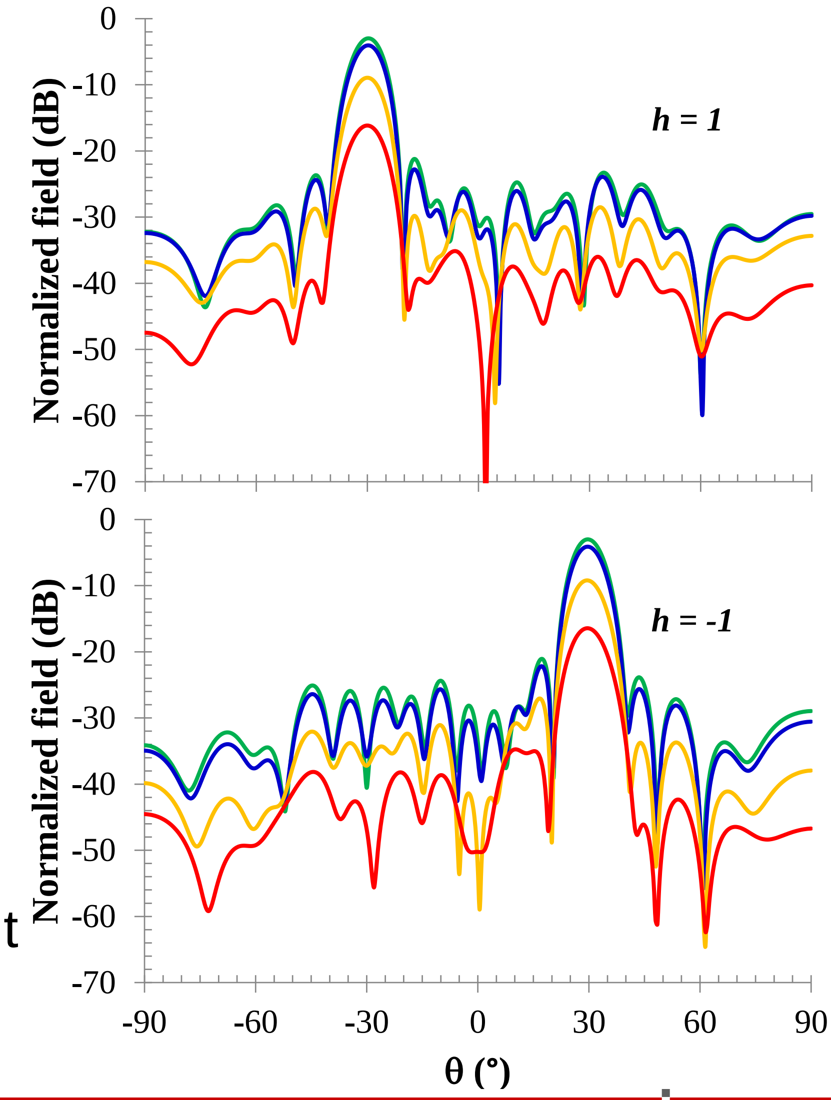




**Simultaneous powering of 3 tags**

# Power handling capabilities

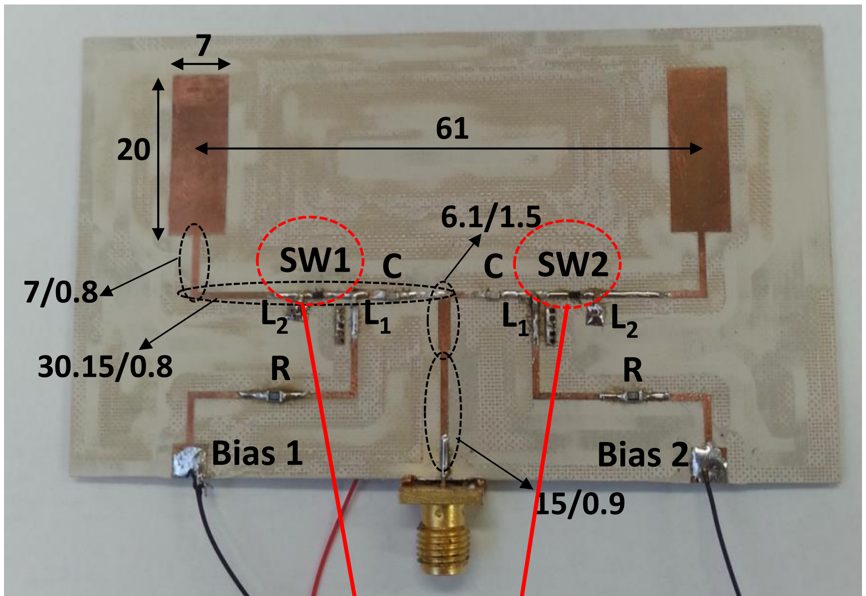
- We consider a real Schottky diode as switching element (Skyworks SMS7630-079)



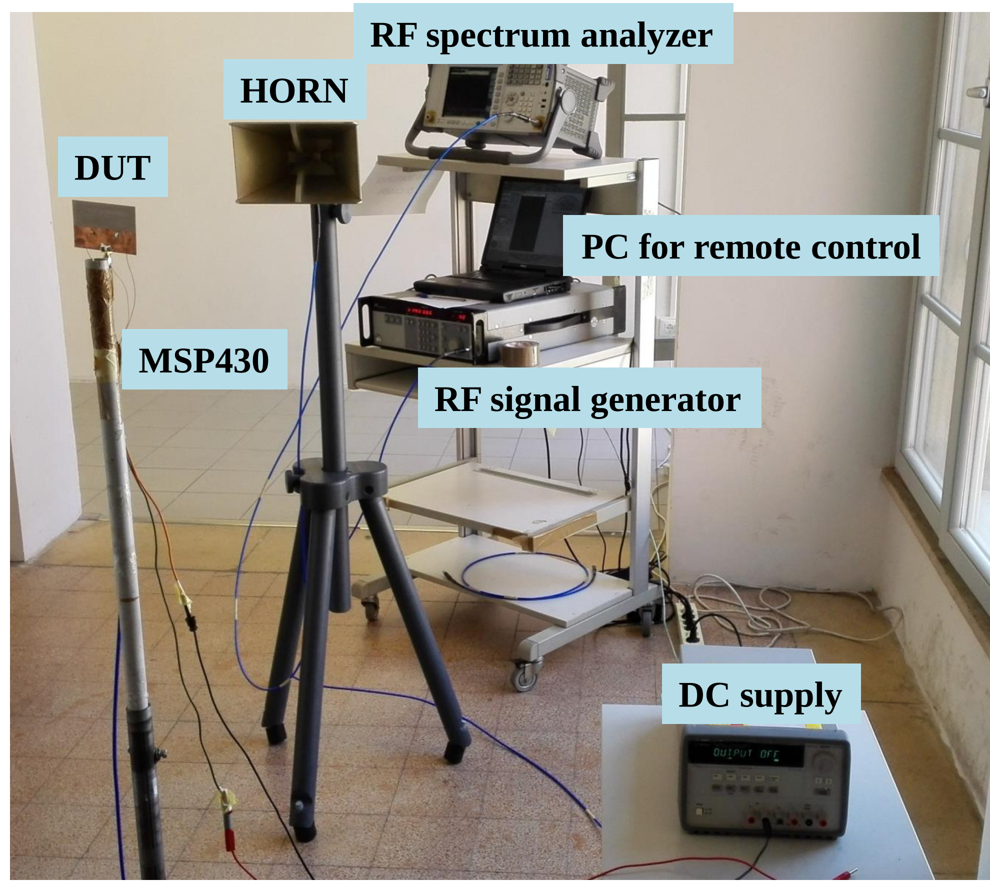




For the medium-power diode in use, the input power limit is about 0 dBm ➡ high-power PIN diodes (e.g. Infineon BAR64-02V)

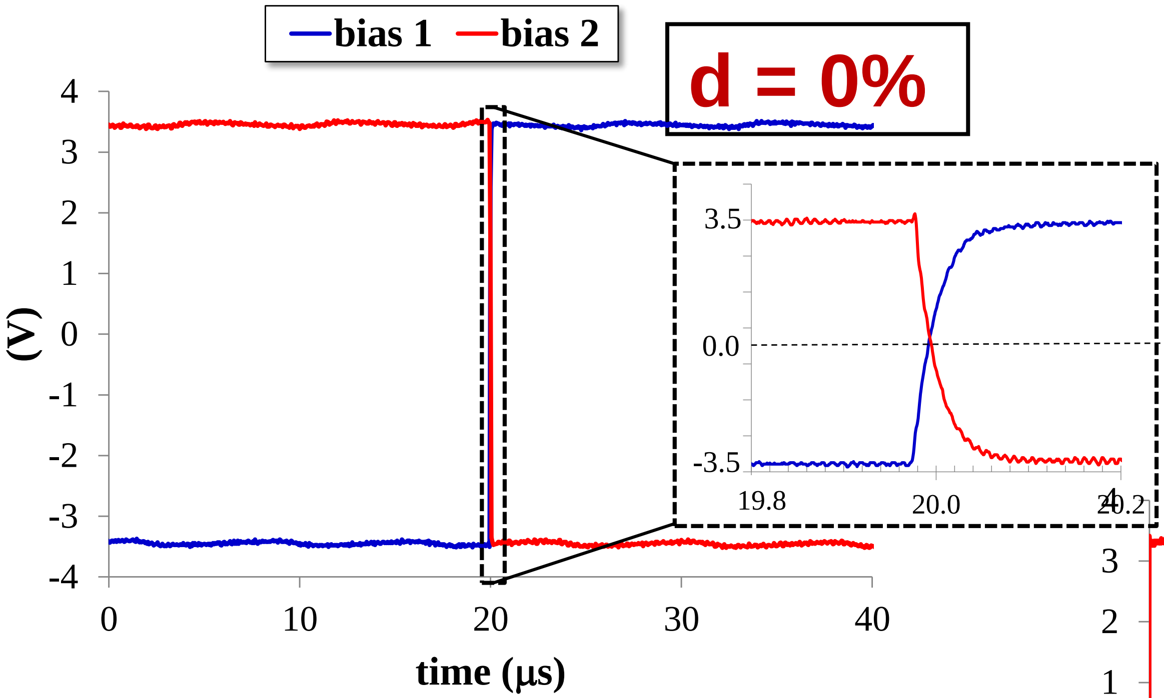
# Prototype and set-up

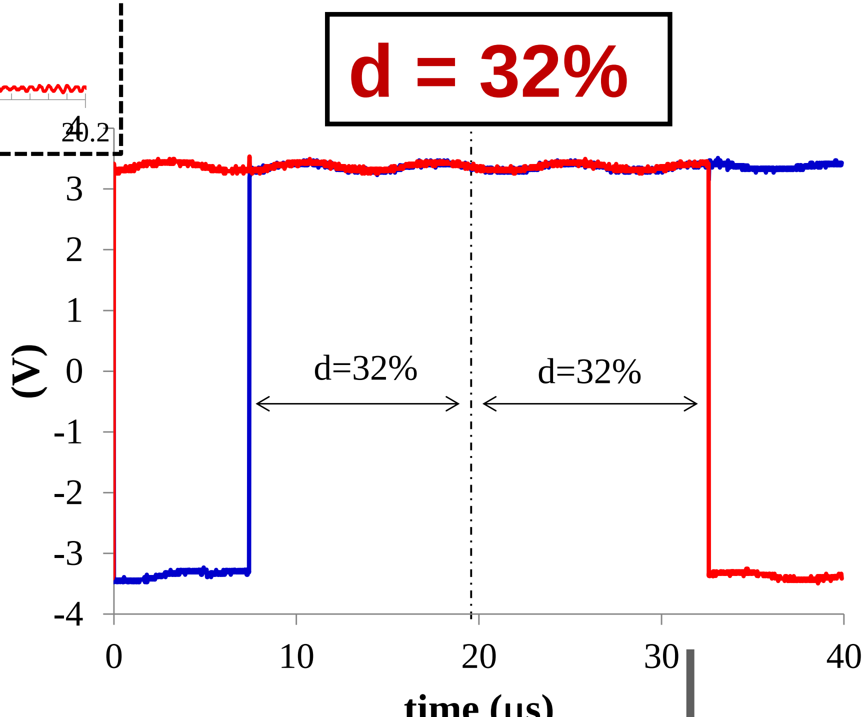



Medium-power Schottky diodes
Skyworks SMS7630-079

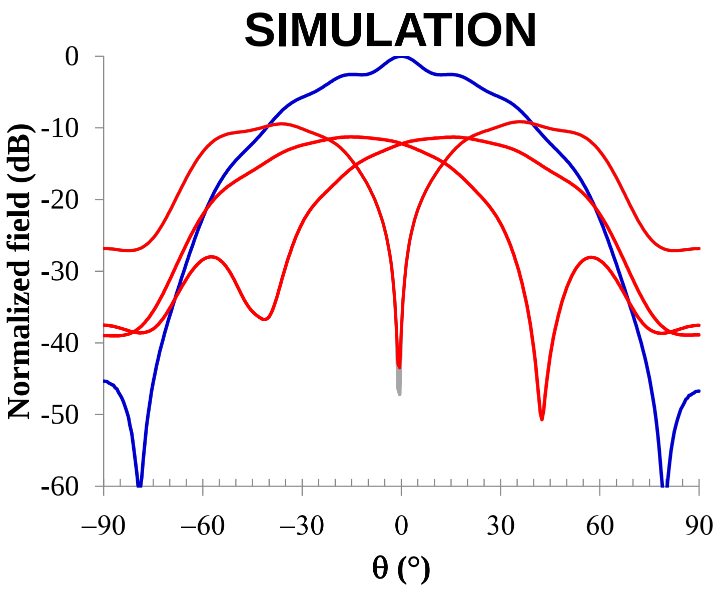


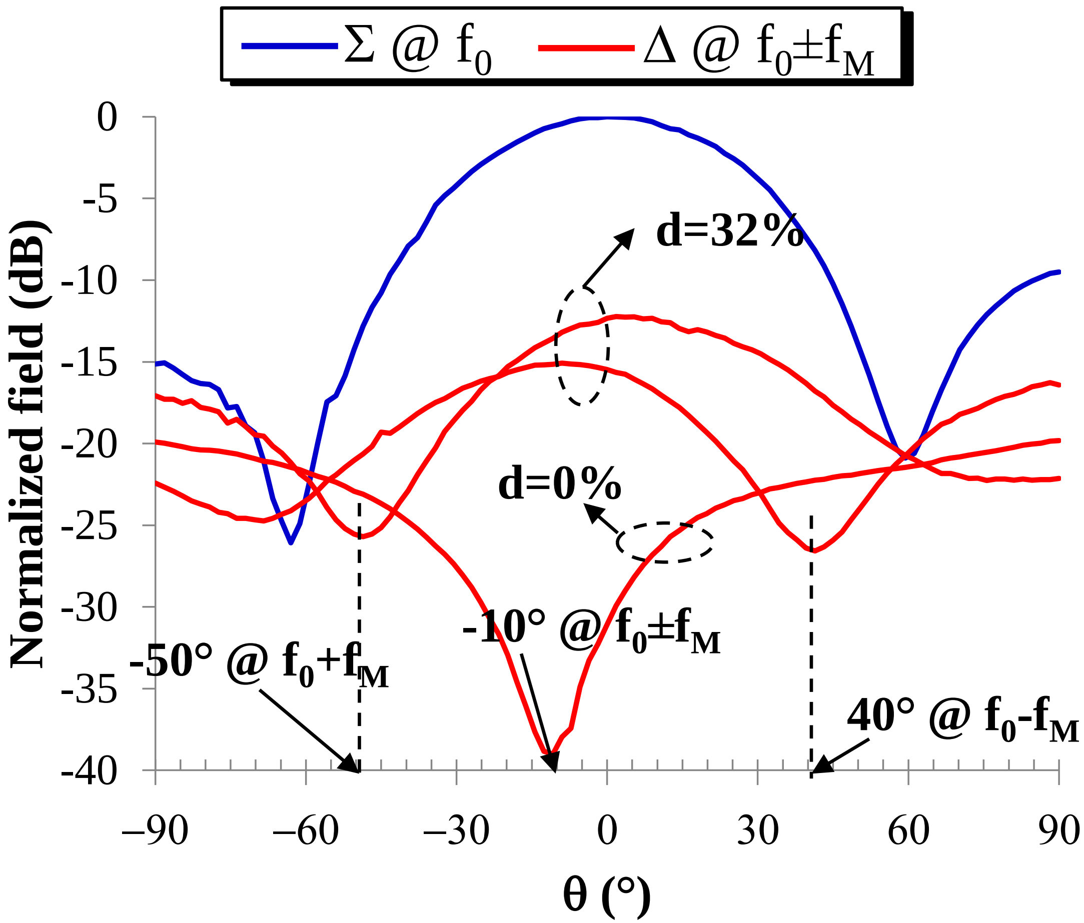
# Real waveform sequences for localization



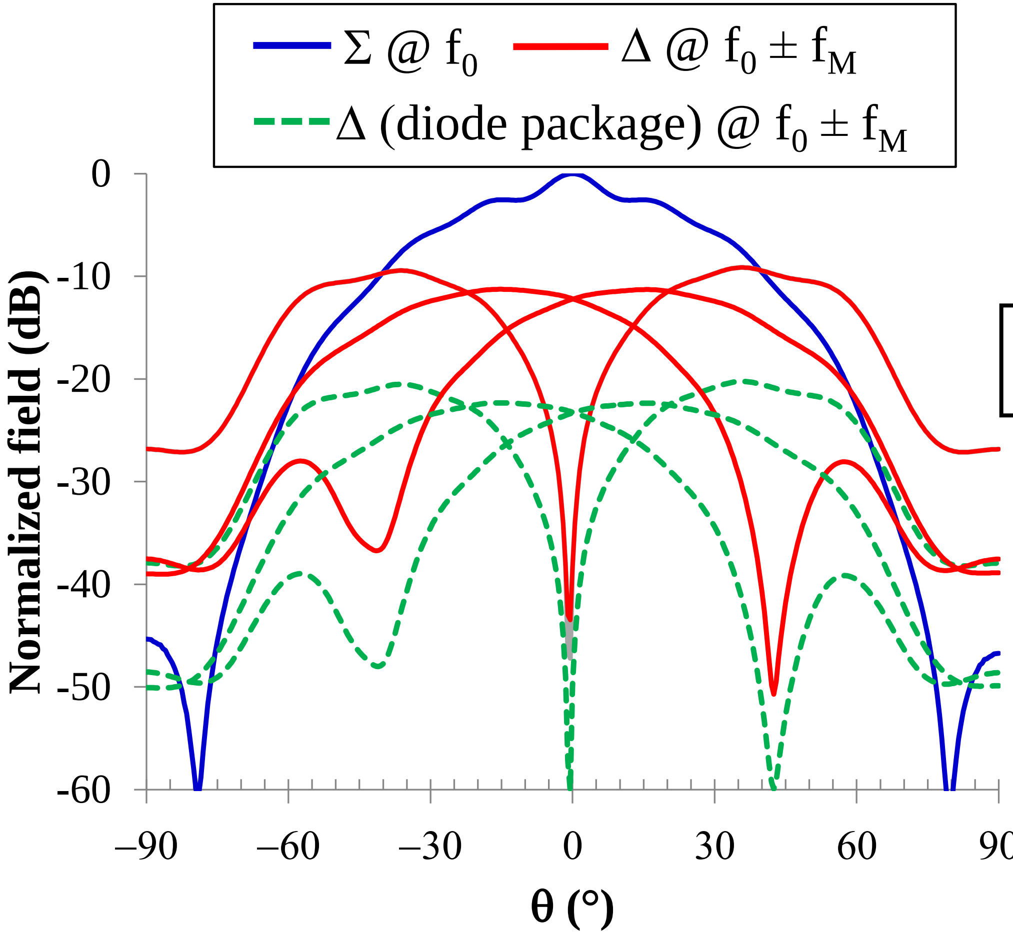
# Measured radiation patterns




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

# Simulated radiation patterns



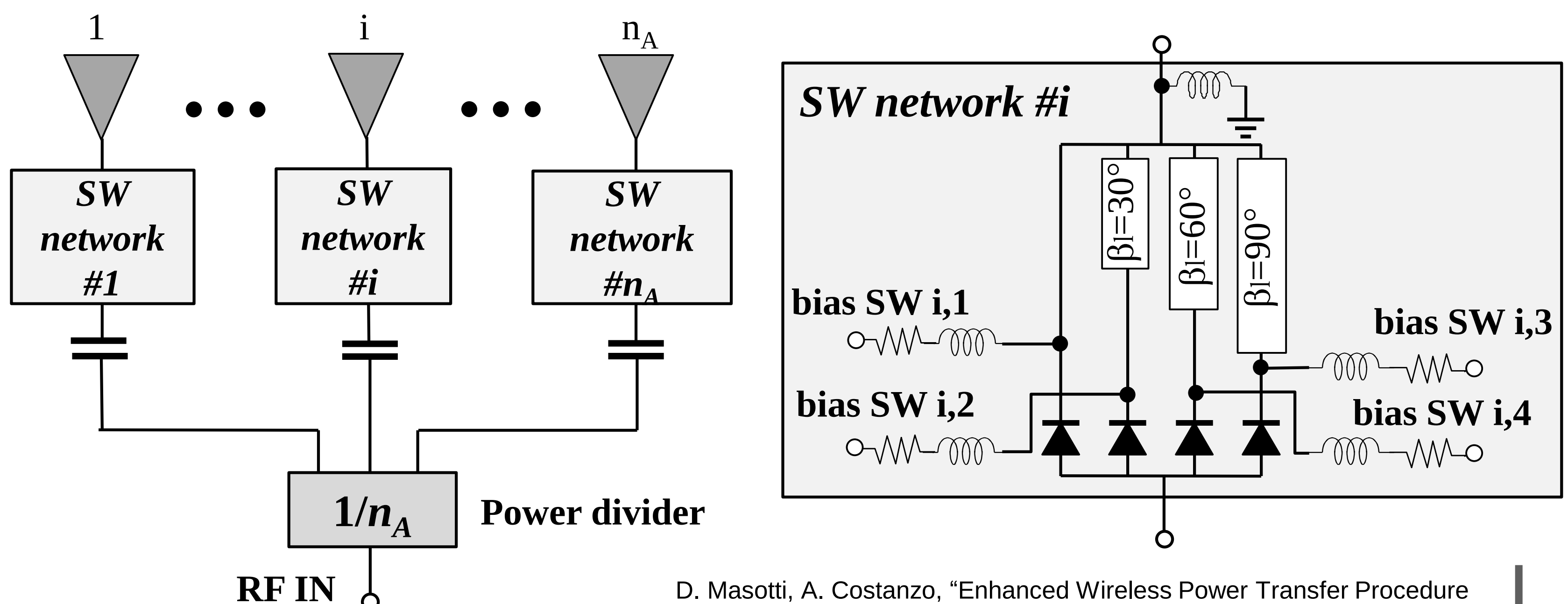

**d = 0%, 32 %**

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

# Hybrid TMA for WPT

WIPE
COST IC1301

- **TMA** suffer from a limitation: the radiation surface at the fundamental carrier can be arbitrarily shaped, but ***cannot be steered*** (because of the real nature of the AF Fourier coeff.)
- **Solution**: hybrid TMA architecture ***with fixed switching networks***




D. Masotti, A. Costanzo, “Enhanced Wireless Power Transfer Procedure via Real-time Beaming”, accepted at WPTC 2016, May 2016

# Hybrid TMA for WPT

$$AF(\theta,t)=\sum_{i=0}^{n_A-1} A_i U_i\,(t)\,e^{j\beta\left(iL\sin\theta-\ell_{ik}\right)}$$

Array factor at the fundamental $f_0$

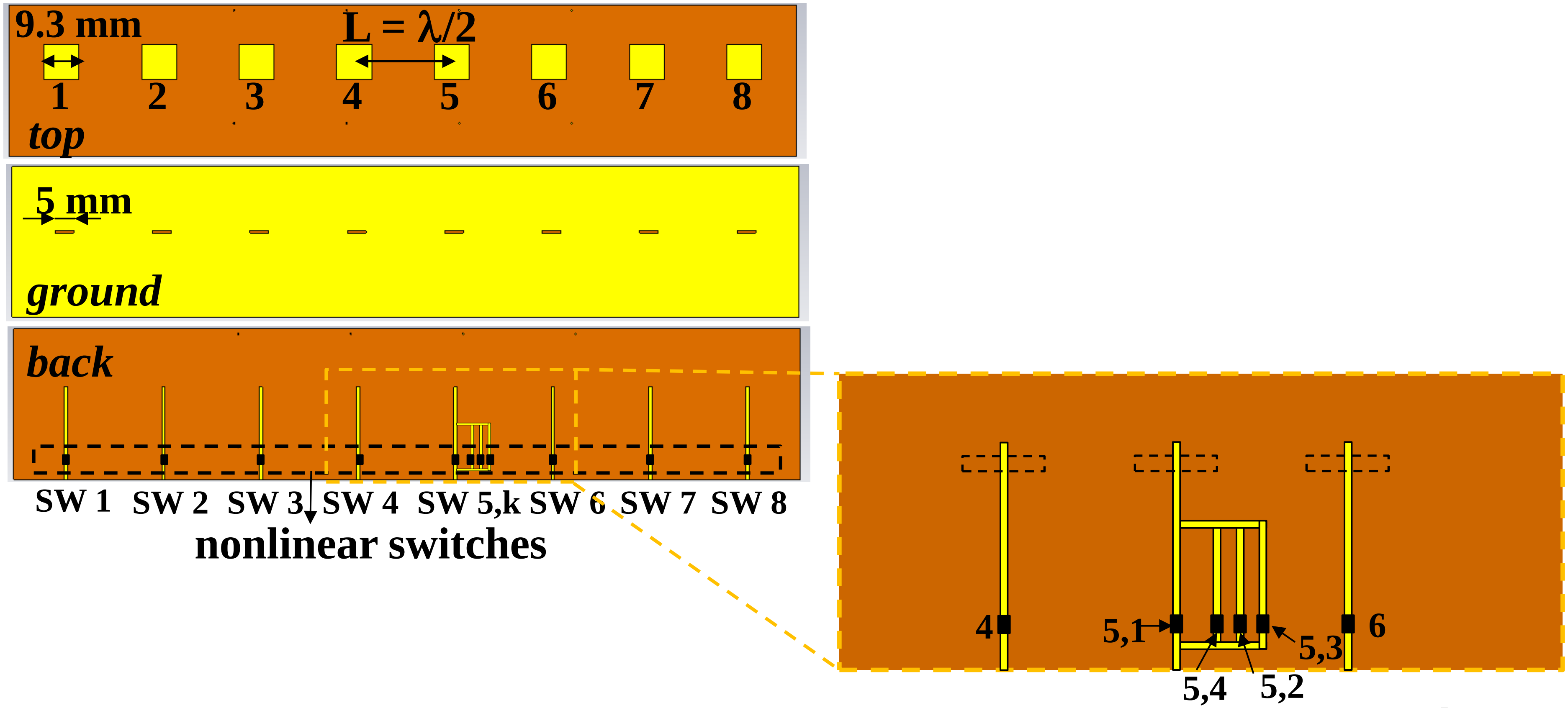
$$AF_0(\theta)=e^{j2\pi f_0 t}\sum_{i=0}^{n_A-1}\tau_i\;e^{j\beta\left(iL\sin\theta-\ell_{ik}\right)}$$

- In this way, the maximum radiation direction at $f_0$ can be a design goal, by acting on the new discrete design parameter $\ell_{ik}$, i.e. by properly biasing the switches of the i-th switching network

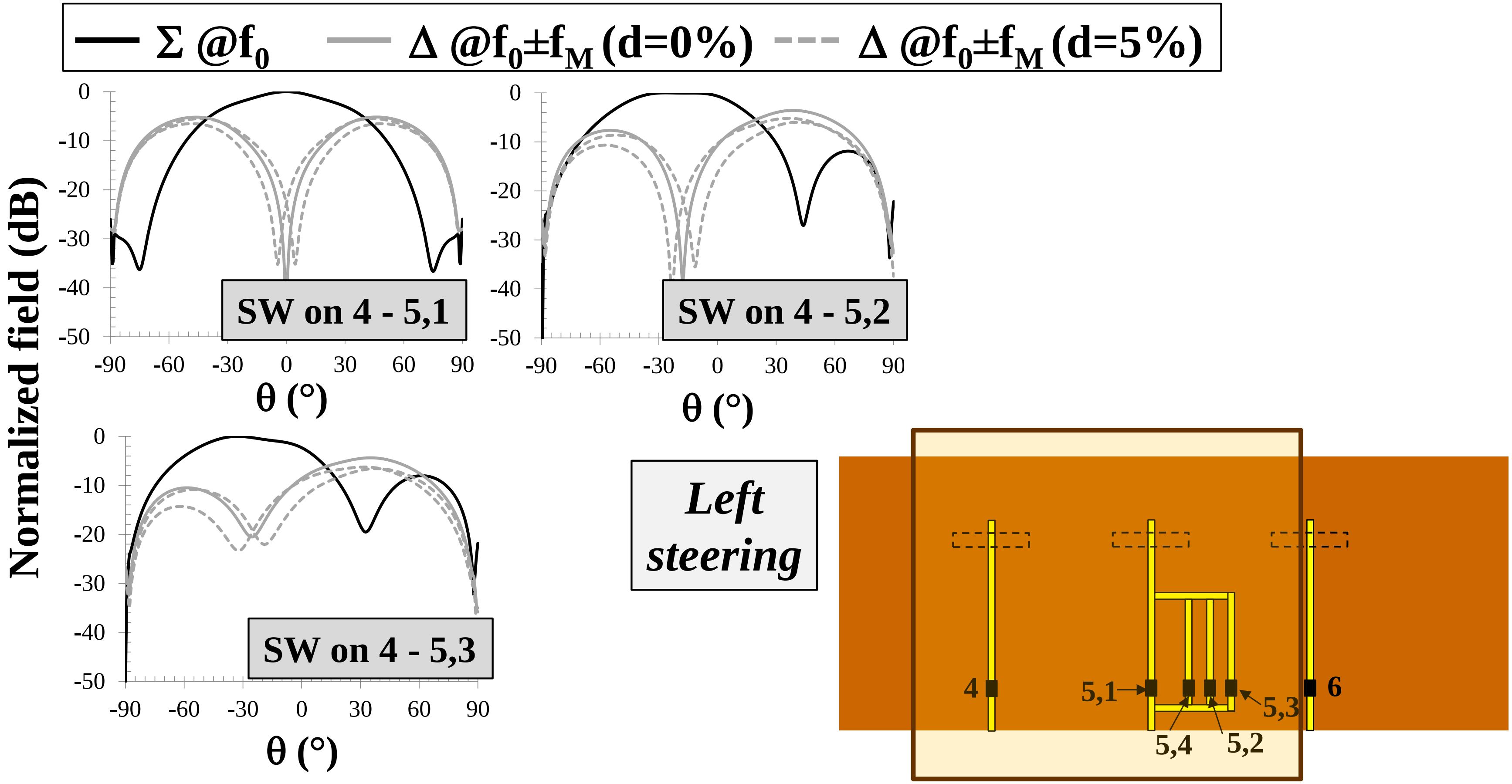
$$\theta_{k,\max}=\arcsin\left(\frac{\lambda\beta\ell_k}{2\pi L}\right)\quad;\quad k=1,\ldots,4$$

# Hybrid TMA: localization

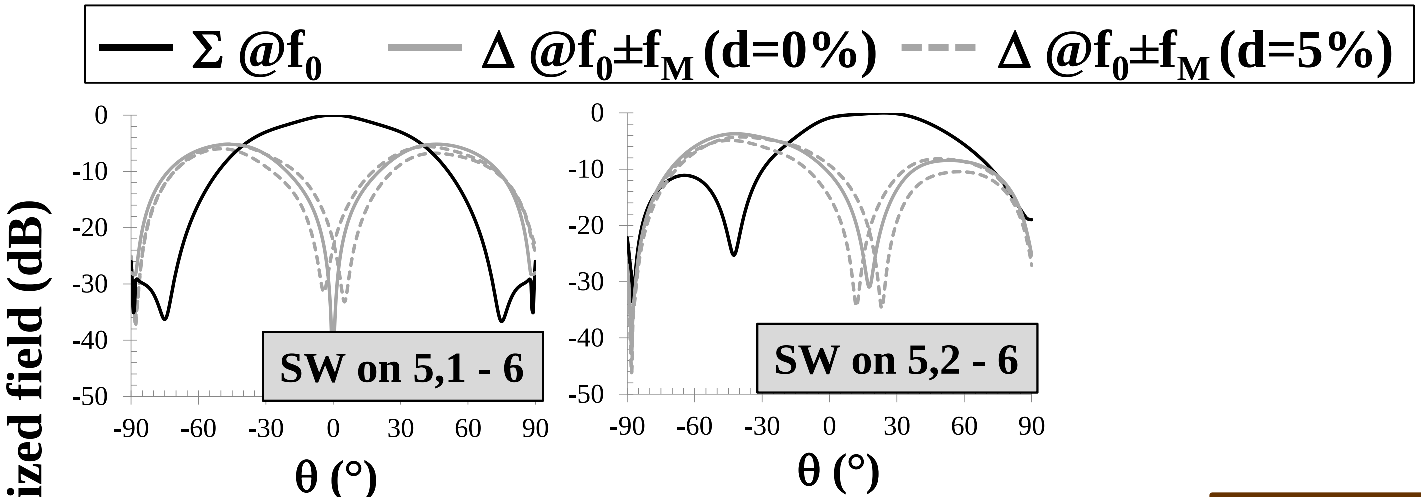
- **8-patch multilayer array**

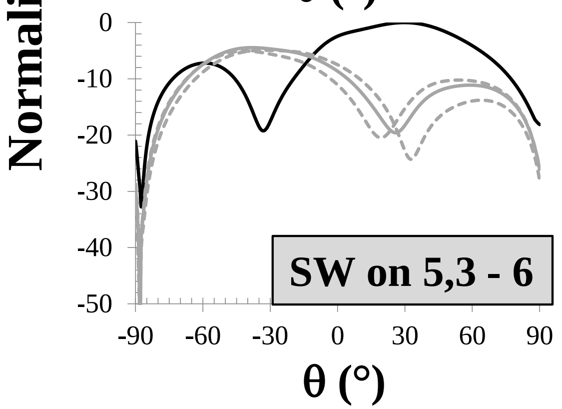


# Hybrid TMA: localization

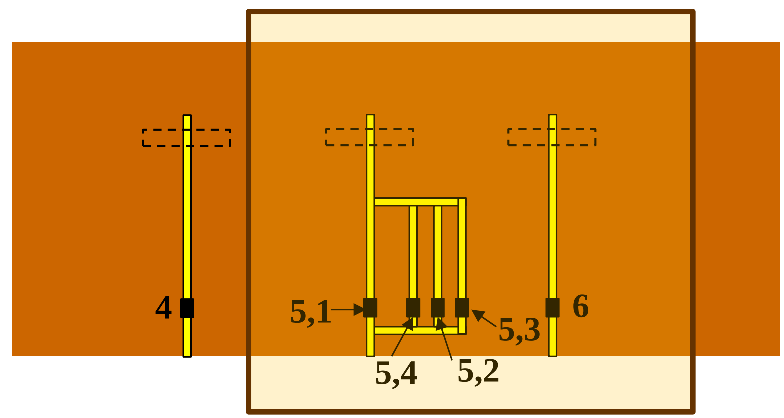


# Hybrid TMA: localization



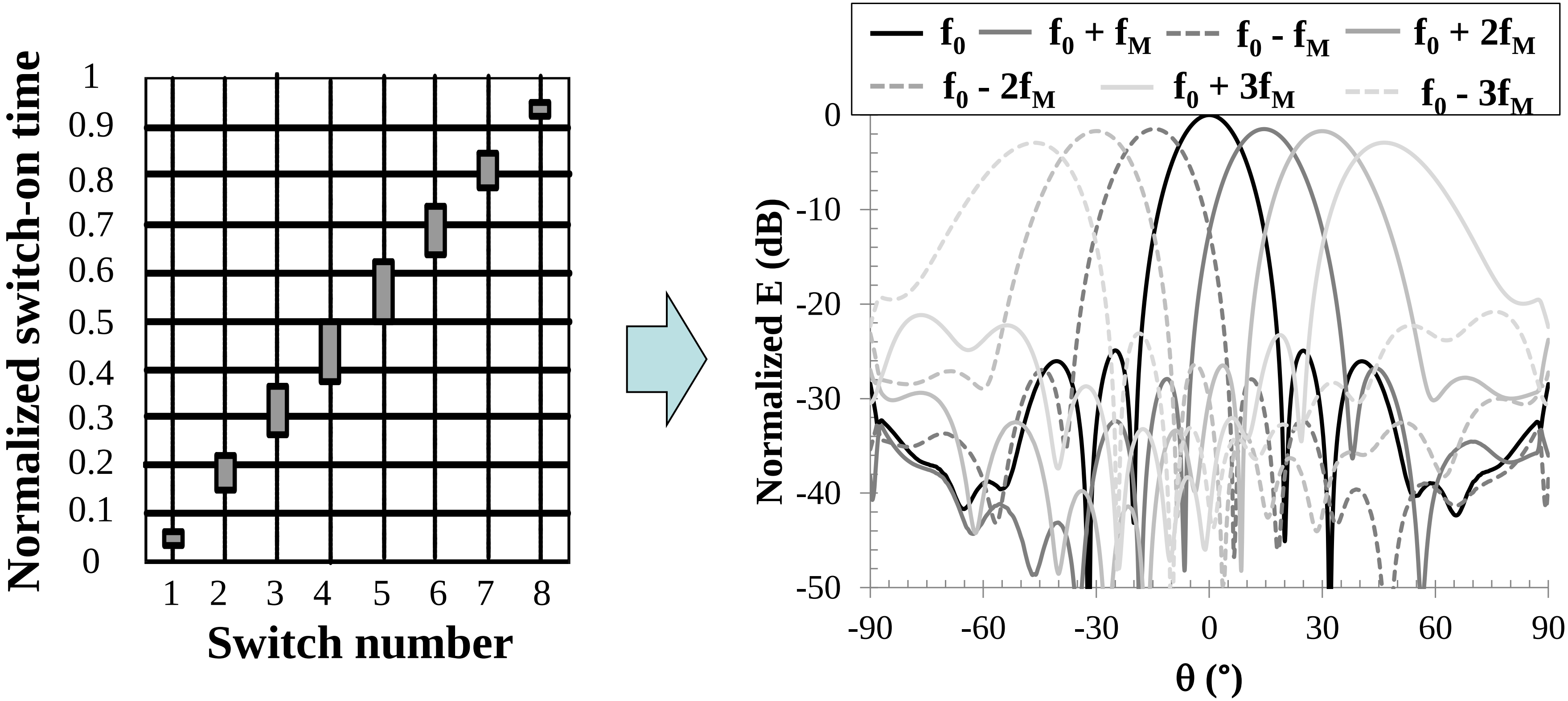




***Right steering***



# Hybrid TMA: WPT to tags

- Case of $\theta_{peak}$ falling into the sectors centered around $\theta_{HPBW}$ = 0°, ±15°, ±30°, ±46°



# Conclusion

- Time-modulated arrays demonstrate an unreachable, ***almost real-time*** reconfiguration
- This versatility can be exploited, in conjunction with the sideband radiation capability, for a ***smart WPT procedure***
- The ease of implementation of these arrays (no phase shifters) makes TMAs a potential candidate for modern wireless applications
- The complexity of these radiating systems implies the need for a rigorous CAD approach in TMA design

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