Time-modulated arrays for smart WPT

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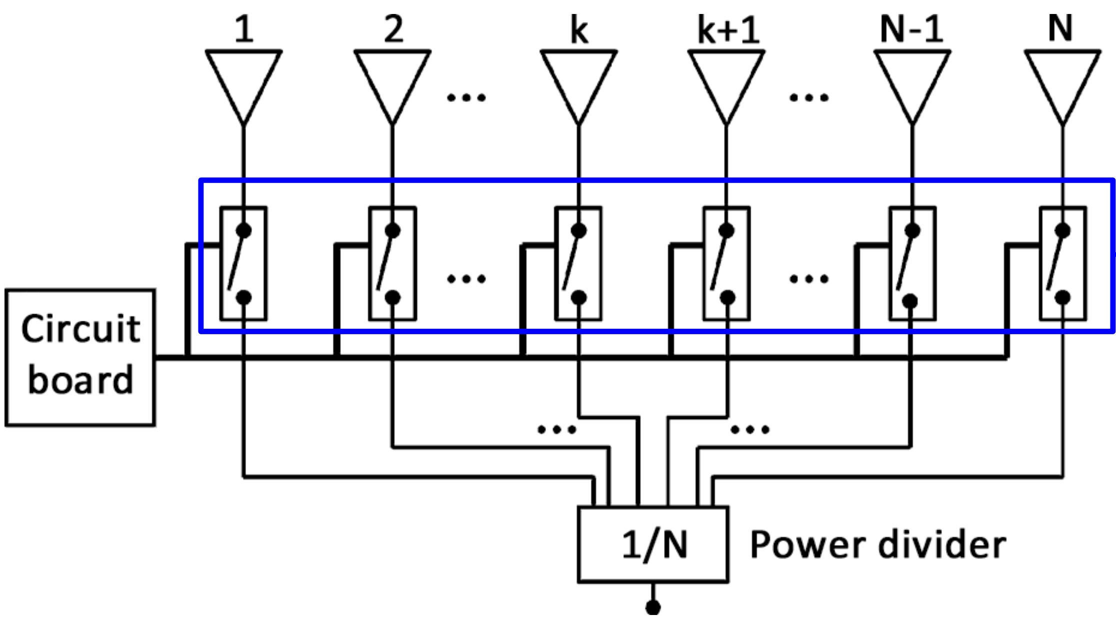
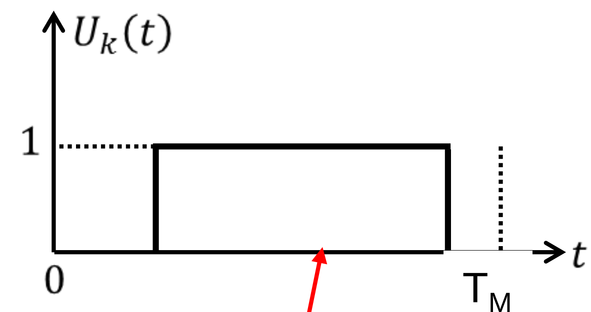
Outline

- ***Time-modulated arrays (TMAs)*** architecture
- TMAs possible applications
- Description of the nonlinear/electromagnetic CAD tool for time-modulated array (TMA) analysis/design
- ***Smart WPT*** with TMA

TMA architecture



Switches controlled by pulse sequences



Array factor of a standard linear array

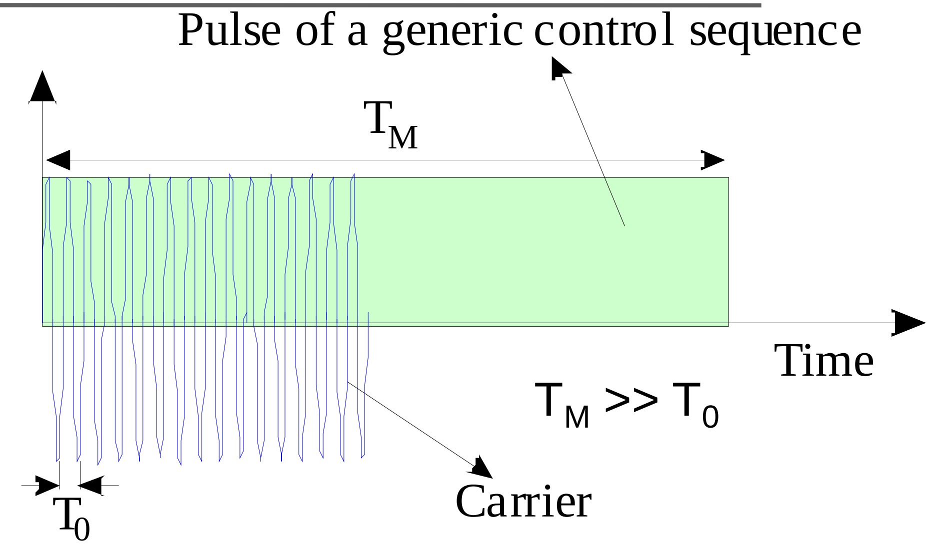
$$AF(\theta,\phi)=\sum_{k=1}^{N}\Lambda_k\, e^{j\delta_k}\, e^{jk\beta L\cos\psi}$$

Array factor of a linear TMA

$$AF(\theta,\phi,t)=\sum_{k=1}^{N}\Lambda_k\, e^{j\delta_k}\, U_k(t)\, e^{jk\beta L\cos\psi}$$

TMA regime

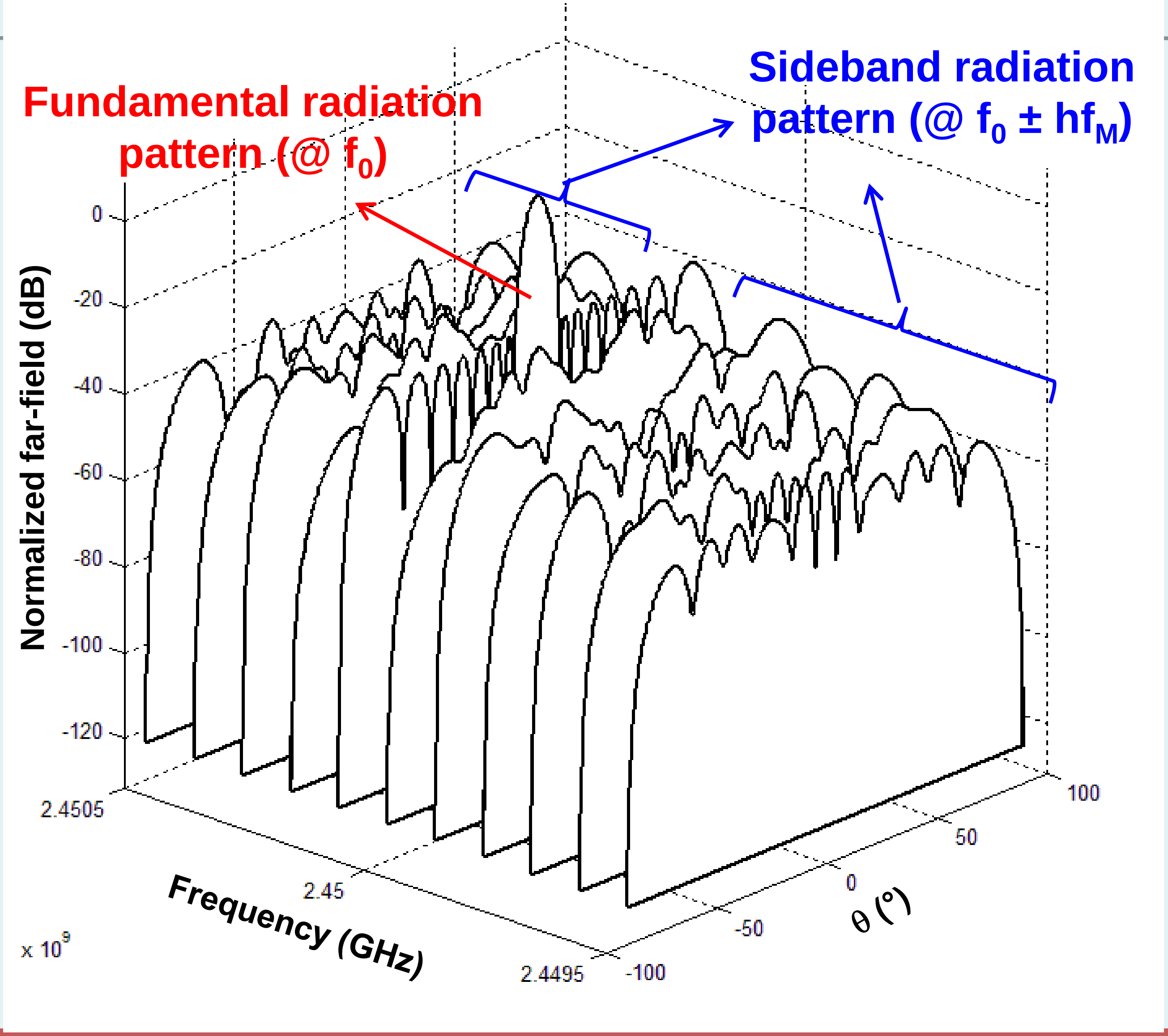
- T_M, f_M : period and frequency of switch modulation
- T_0, f_0: period and frequency of ***sinusoidal*** RF carrier



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

The superimposed switch modulation makes the array able to radiate not only at the ***fundamental carrier (h=0)***, but also at the ***sideband harmonics (h≠0)***

TMA radiation



TMA high reconfigurability

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

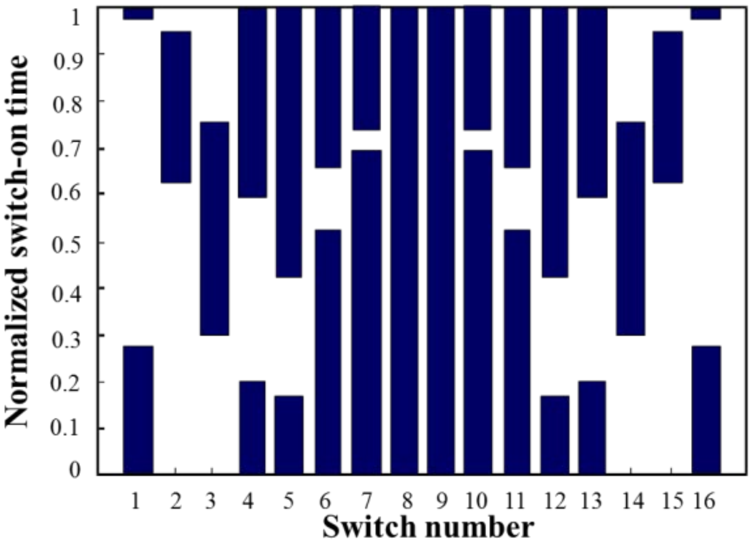
- The ease of implementation (no phase-shifters)
- The fast software control

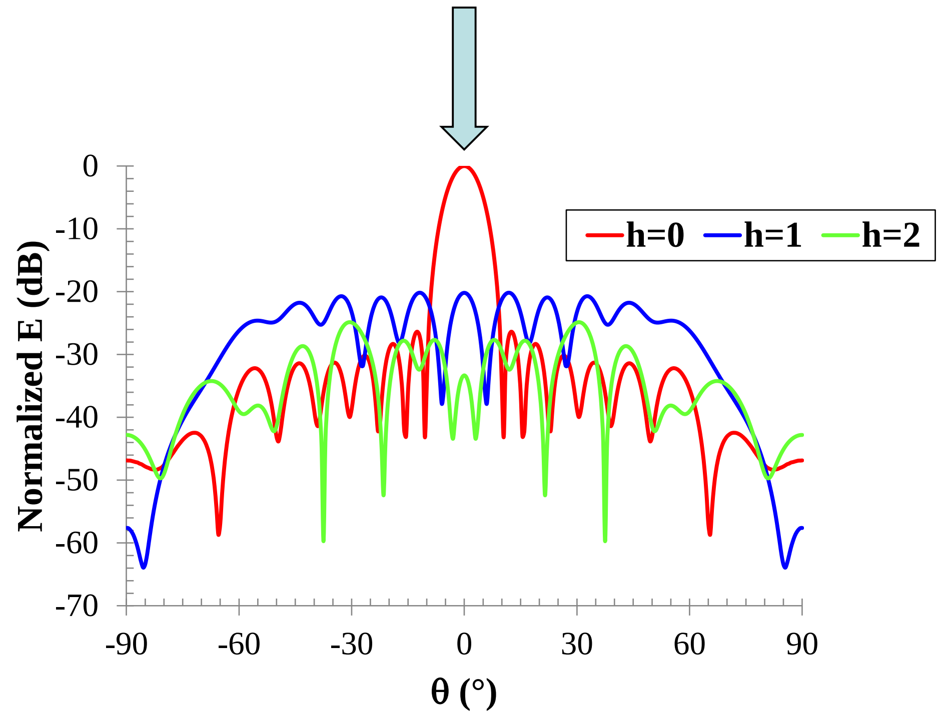
Antenna reconfiguration in real time!

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

TMA applications

- Reduce self-interference in the broadside direction (θ=0°) due to the desired signal received @ $f_0 \pm hf_M$ ($h \neq 0$) (***Sideband radiation suppression***)

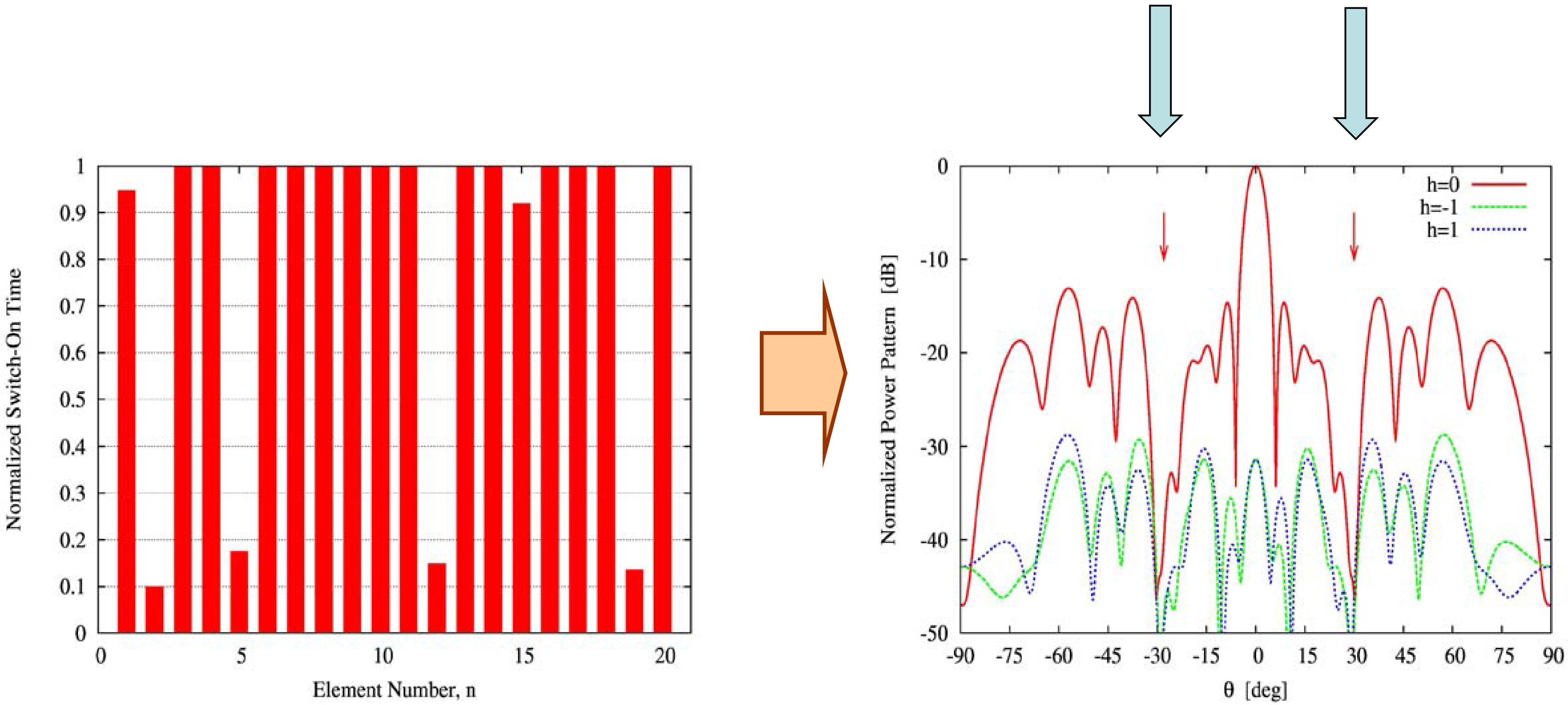




L. Poli, P. Rocca, L. Manica, A. Massa, "Pattern synthesis in time-modulated linear arrays through pulse shifting," *IET Microwaves, Ant. & Prop.*, vol. 4, no. 9, pp. 1157-1164, Sept. 2010

TMA applications

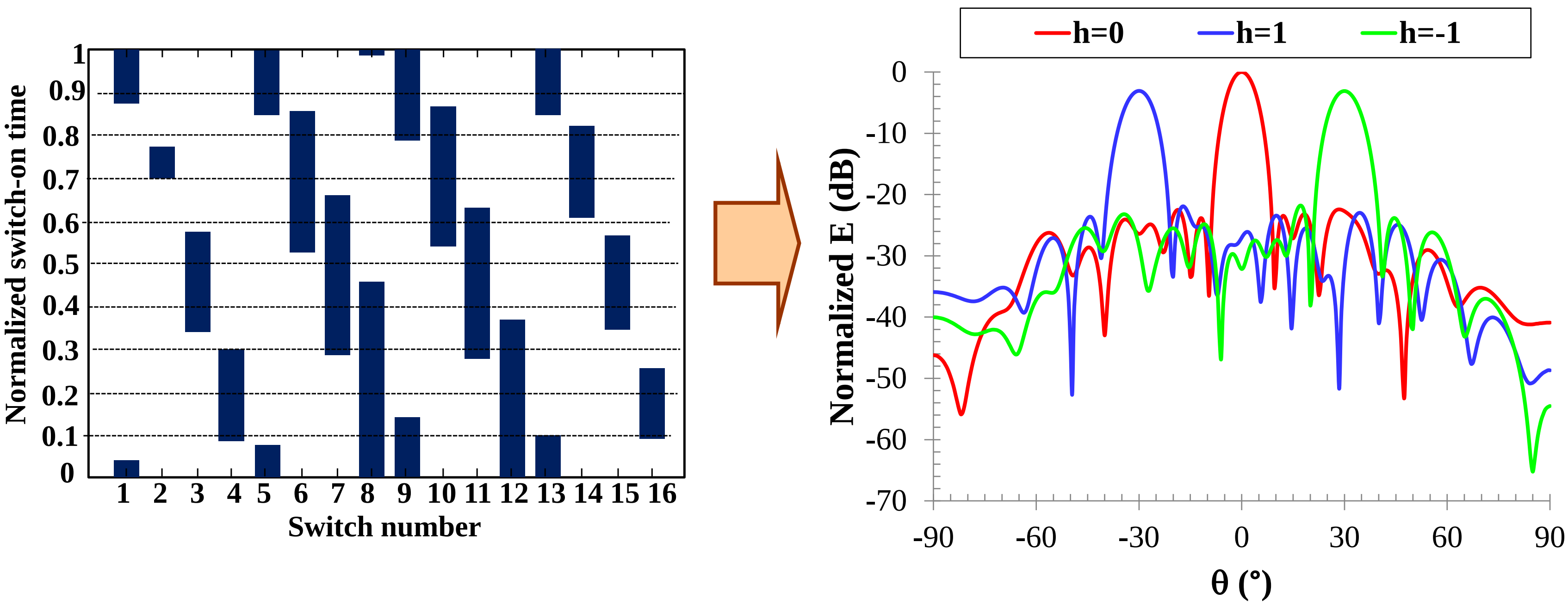
- Suppress undesired interference coming from $\theta \neq 0°$ @ $f_0 \pm hf_M$ ($h = 0, 1, 2, \ldots$) (***Harmonic nulling***)



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 applications

- Exploitation as a multi-channel system (***Harmonic beamforming***)



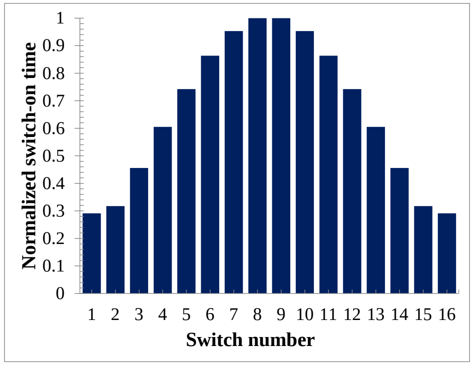
L. Poli, P. Rocca, G. Oliveri, A. Massa, "Harmonic beamforming in time-modulated linear arrays through particle swarm optimization", *IEEE Trans. Ant. & Prop.*, vol. 59, no. 7, pp. 2538-2545, July 2011

TMA optimization

- TMA design methods focus on control sequence optimization

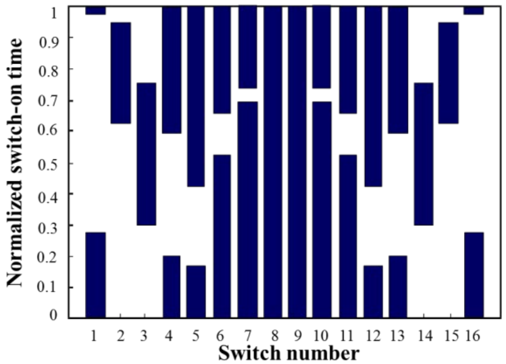
Ideal radiating elements
Ideal control switches

Variable Aperture Size (W. H. Kummer et al. 1963)



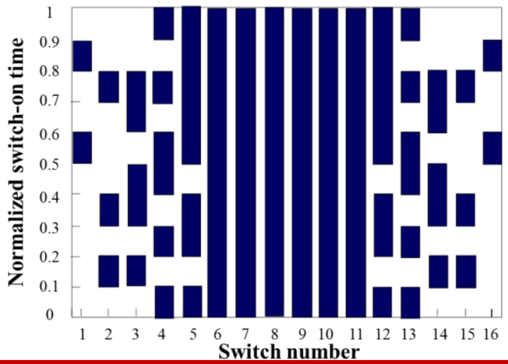
design parameter:
impulse length

Pulse Shifting (L. Poli et al. 2010)



design parameters:
impulse length
switch-on instant

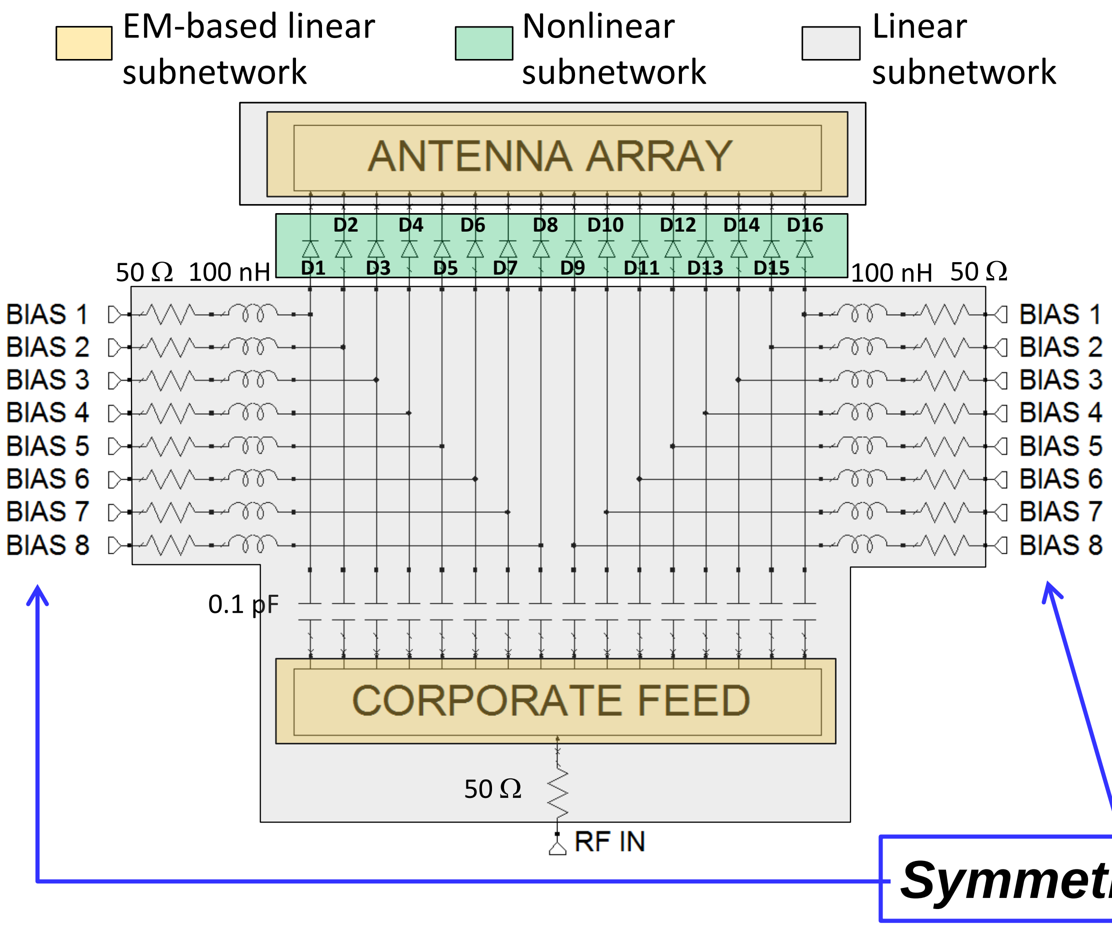
Binary Optimized Time Sequences
(S. Yang et al. 2005)



design parameter:
impulse sub-intervals

NL/EM TMA co-simulation

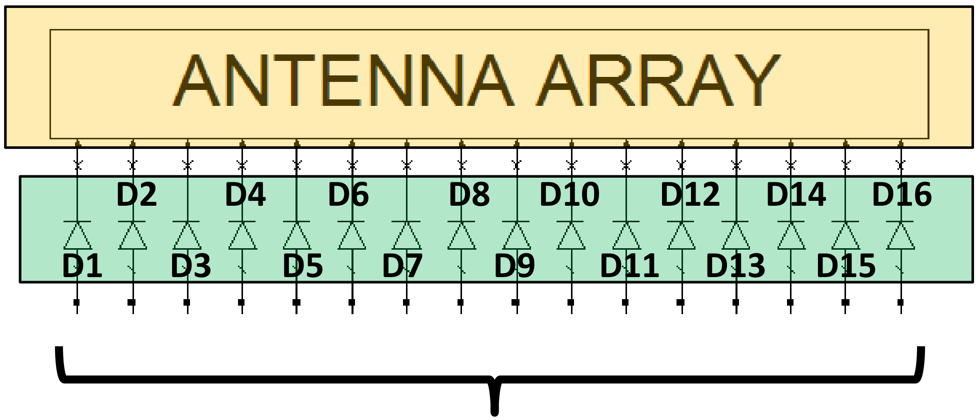
Piecewise Harmonic-Balance method



- A ***nonlinear*** subnetwork, containing the diodes
- A ***linear*** subnetwork, including
  - the EM-based part (the array and the feeding network, in the present case)
  - the lumped components used for biasing and DC-blocking

NL/EM TMA co-simulation

Modulated far-field evaluation



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

⇩

circuit-envelope HB

fast carrier time

harmonics of the unmodulated regime

slow modulation time

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

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

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

no. of harmonics for modulation spectrum description

NL/EM TMA co-simulation

Field envelope at the fundamental harmonic

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

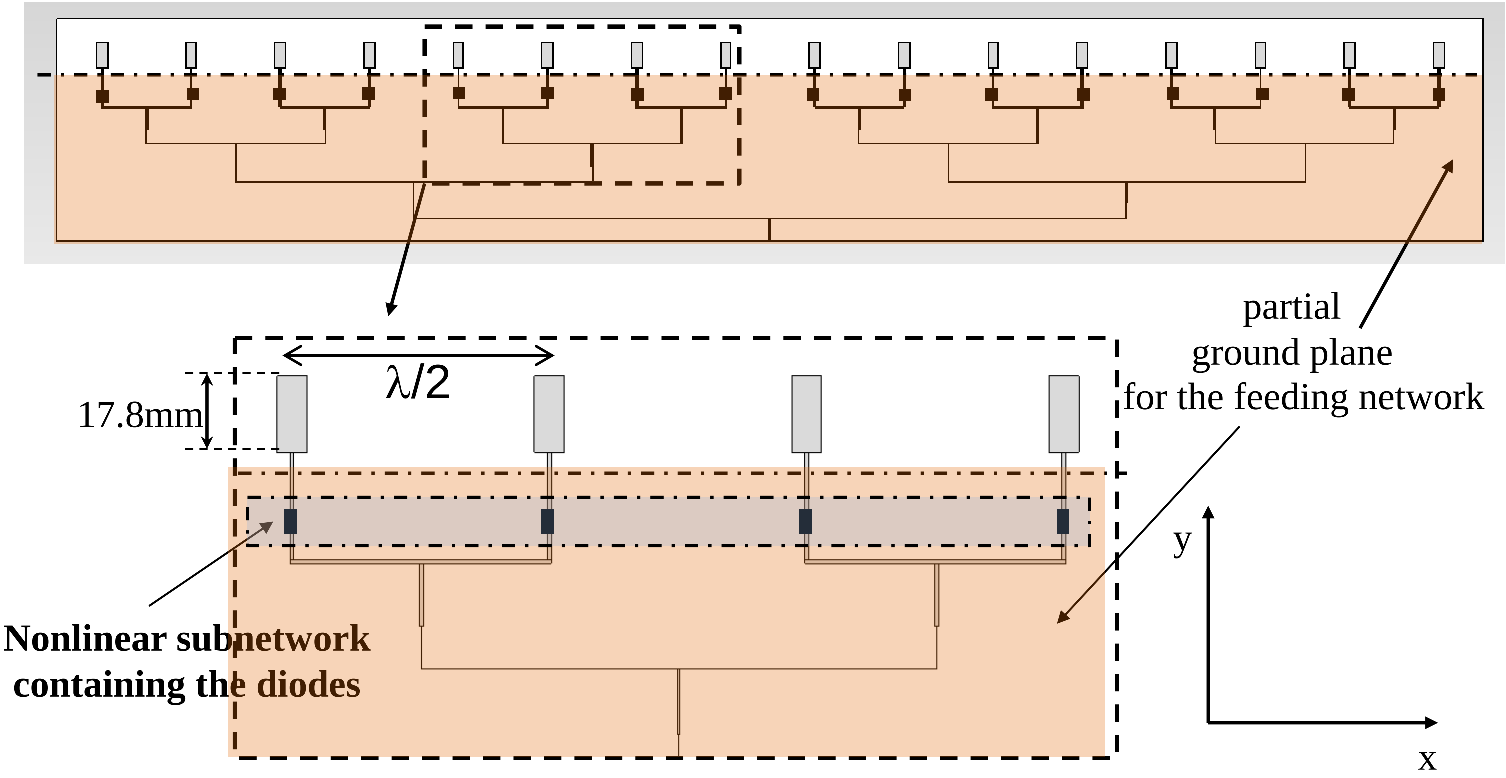
$$\bullet \sum_{i=1}^{n_A}\left[\hat{\boldsymbol{\theta}}\, A_\theta^{(i)}(\theta,\phi;\omega_0) + \hat{\boldsymbol{\phi}}\, A_\phi^{(i)}(\theta,\phi;\omega_0)\right] I_{A,1}^{(i)}(t_M) -$$

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

- $A_\theta^{(i)}$, $A_\phi^{(i)}$ ⇨ ***EM data-base***
  - are the scalar components of the normalized field
  - are generated by EM simulation with only the i-th monopole excited by a unit-current sinusoidal source of angular frequency ω_0
- The EM analyses are carried out ***once for all***

Co-simulation results

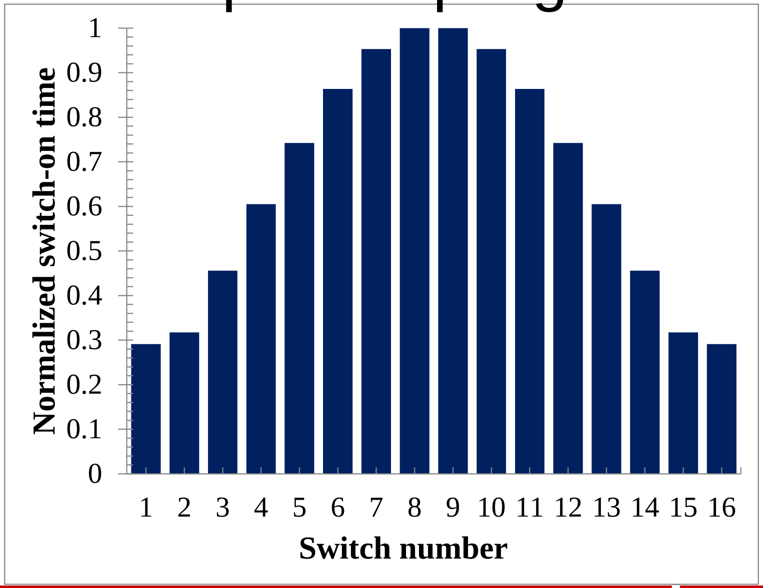
- 16-monopole planar linear array operating at f_0=2.45 GHz
- The substrate is a 0.635 mm-thick Taconic RF60A (ε_r = 6.15, tanδ=0.0028 @ 10GHz)



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.

TMA with Dolph-Chebyshev pattern

- Sinusoidal carrier **f_0 = 2.45 GHz**, P_{RF} = 0dBm
- Switch modulation frequency **f_M = 10 kHz** ($f_M \ll f_0$)
- Rectangular pulses with repetition period T_M = 0.1 ms 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



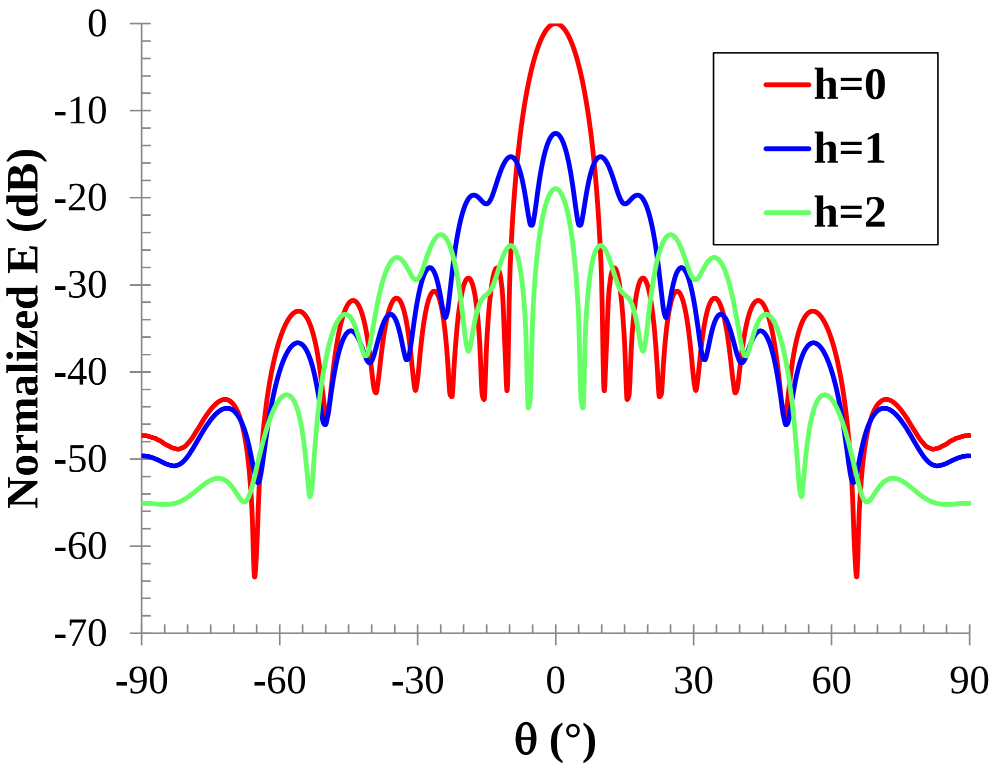
Radiation patterns

$$\boldsymbol{E}_k(t_M) = \sum_{h=-N_B}^{N_B} \boldsymbol{E}_{kh} \exp(jh\omega_M t_M)$$

- k=1, h=0: 2.45 GHz fundamental

- k=1, h=1: 2.45001 GHz first harmonic

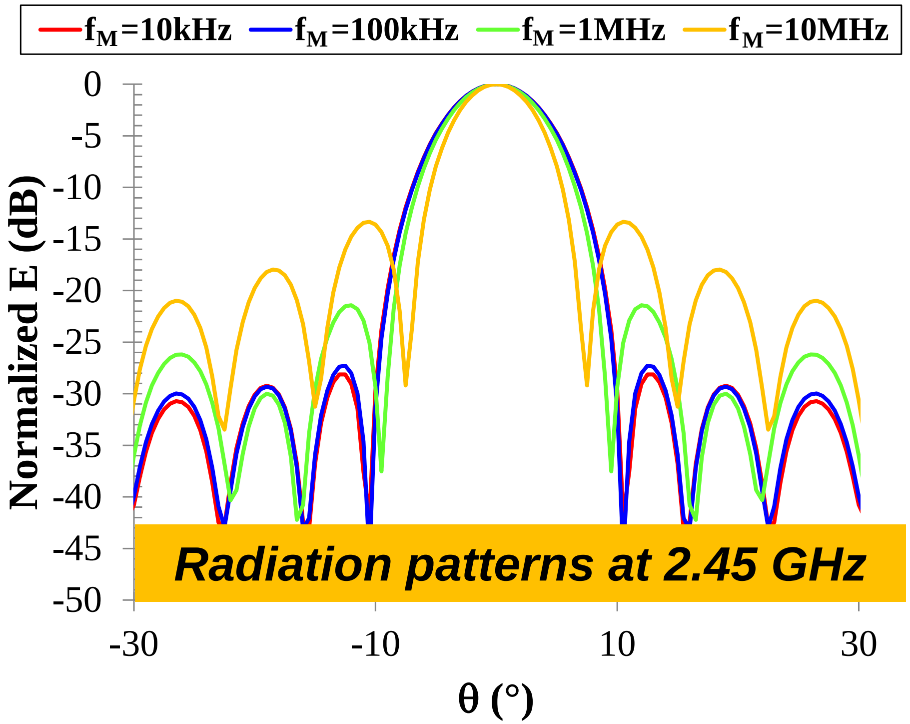
- k=1, h=2: 2.45002 GHz second harmonic

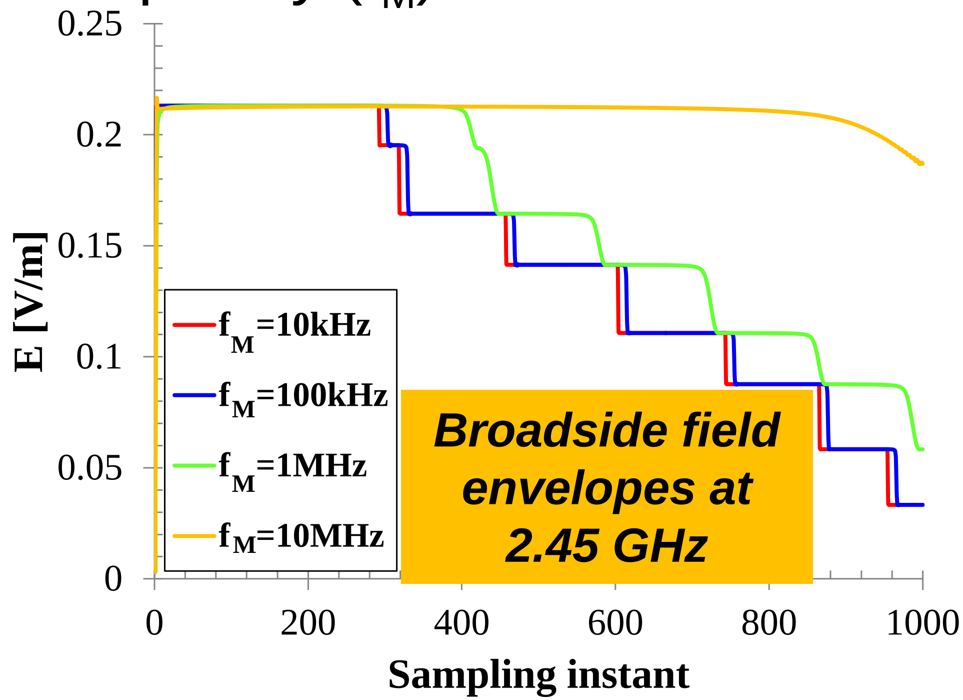


Known problem of VAS sequences: unwanted ***sideband radiation***

Modulation frequency range

- Control sequence modulation frequency (f_M) variation



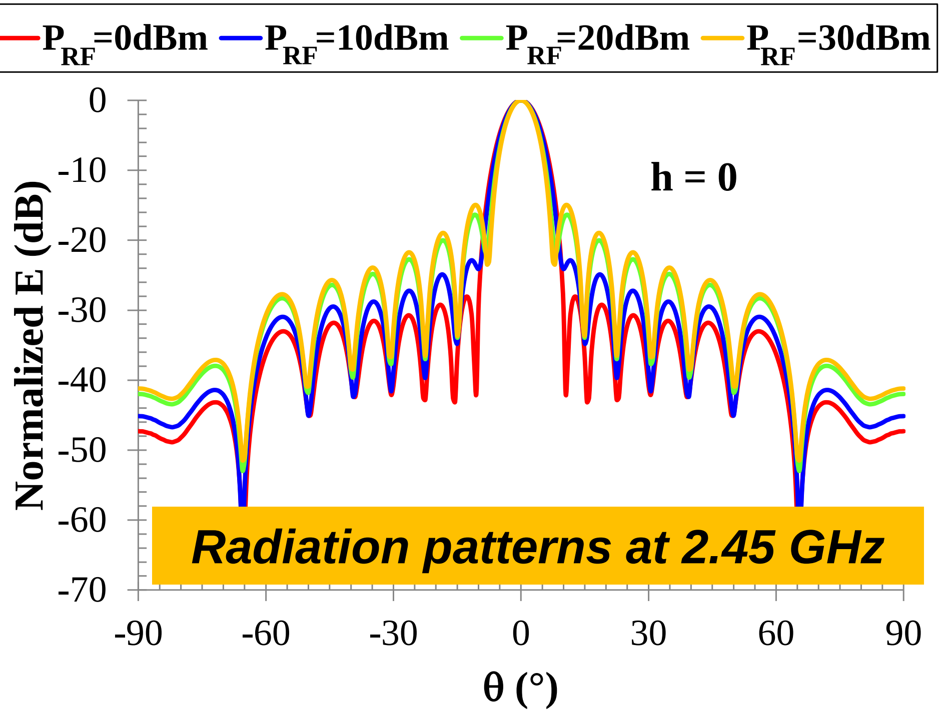


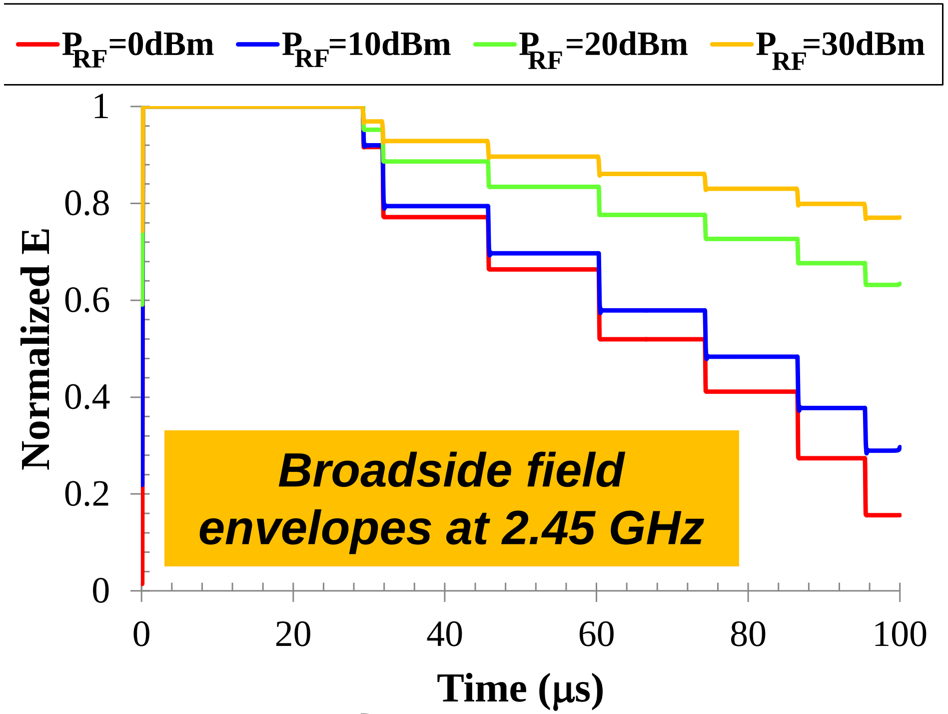
- High values of f_M result in the gradual disappearance of some commutations and unwanted SLL increase

$\Rightarrow$ $f_M^{max} \approx 100\text{kHz}$

Nonlinear diodes effect

- Input power level (P_{RF}) variation



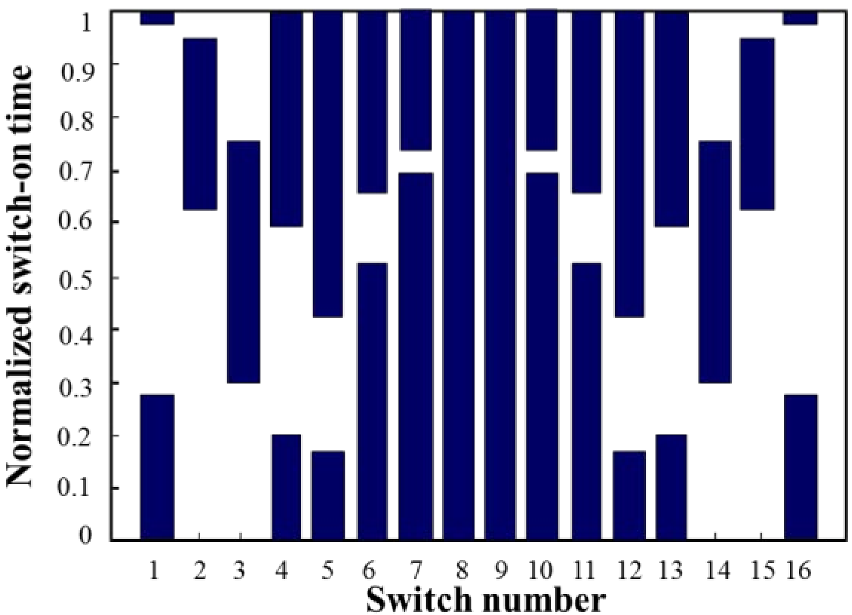


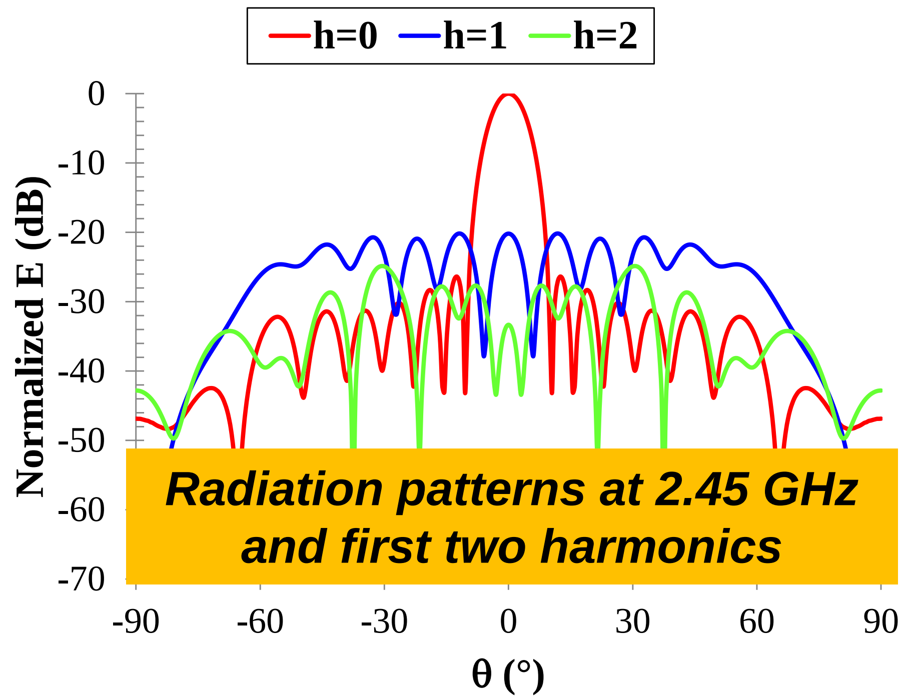
- At high power levels the bias voltage is completely overrun, because a bigger portion of RF signal is rectified by the nonlinear diodes and superimposed to bias

$\Rightarrow P_{RF}^{max} \approx 10\text{dBm}$

TMA with Pulse Shifting pattern

- A symmetric **PS** pulse sequence with SLL = -30 dB is chosen





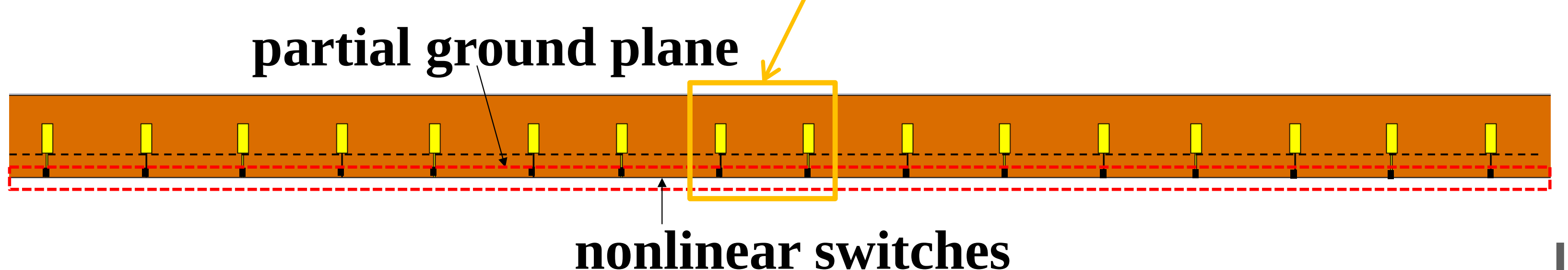
- Note that the time-consuming EM-based database consisting in the $A_\theta^{(i)}$, $A_\phi^{(i)}$ coefficients ***is always the same***

Smart WPT with TMA

- The versatility of TMAs allows a ***smart transfer of power*** by means of a **two-step procedure**

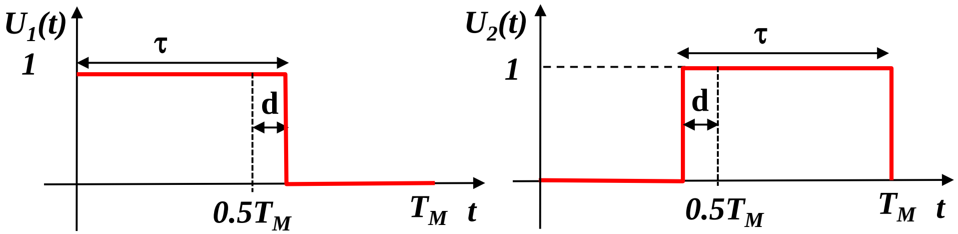
- Scenario: room with randomly placed tagged objects

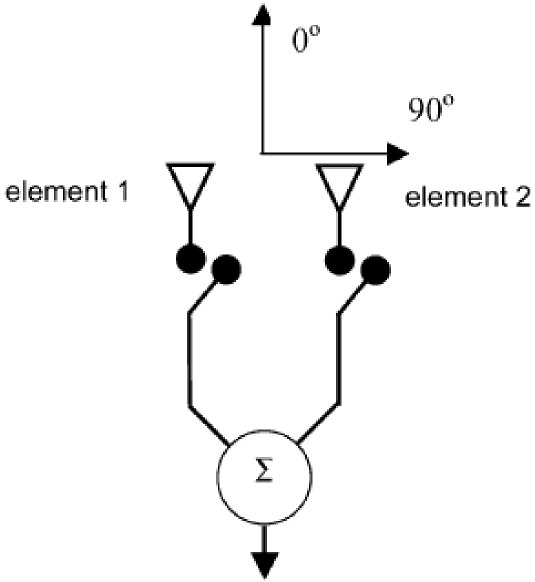
- **1st step:** ***Localization of tags***
  - the sole ***two-inner-element sub-array*** is operating in this phase (the other 14 peripheral switches are left open)



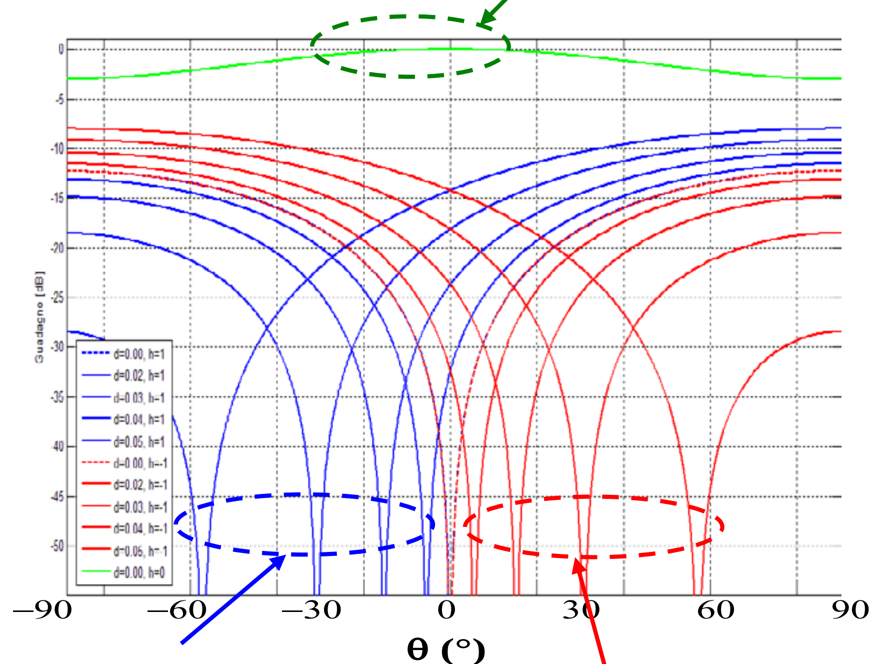
Localization of tags

- By properly driving the switches of an array of two ***isotropic*** elements ***the Δ pattern can be steered***:





Sum (Σ) pattern @ f_0



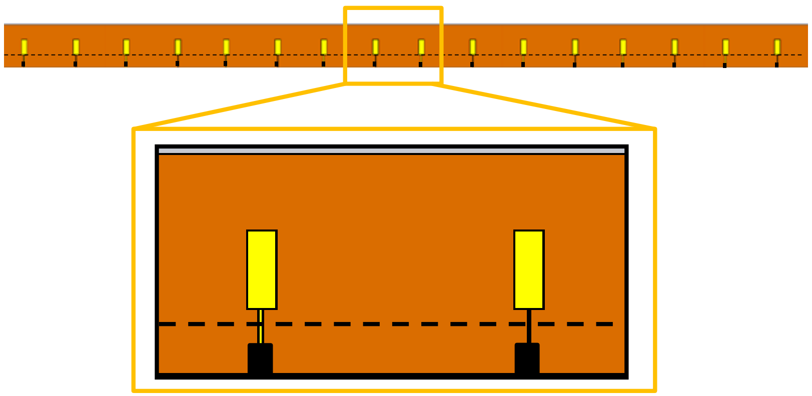
Difference (Δ) pattern @ f_0+f_M

Difference (Δ) pattern @ f_0-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

Localization of tags

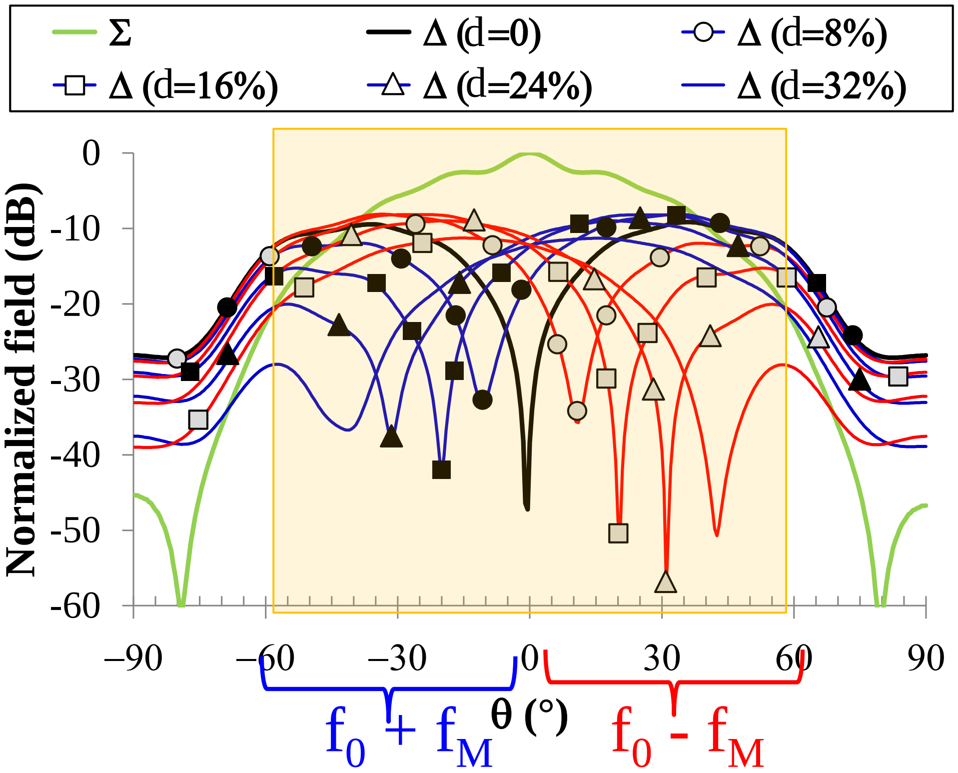
- By properly driving the two inner switches of two ***real*** dipoles:



Received Maximum Power Ratio

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

θ^{i}_{peak}; *i=1,…,* N_{tag} ***List of tags position***



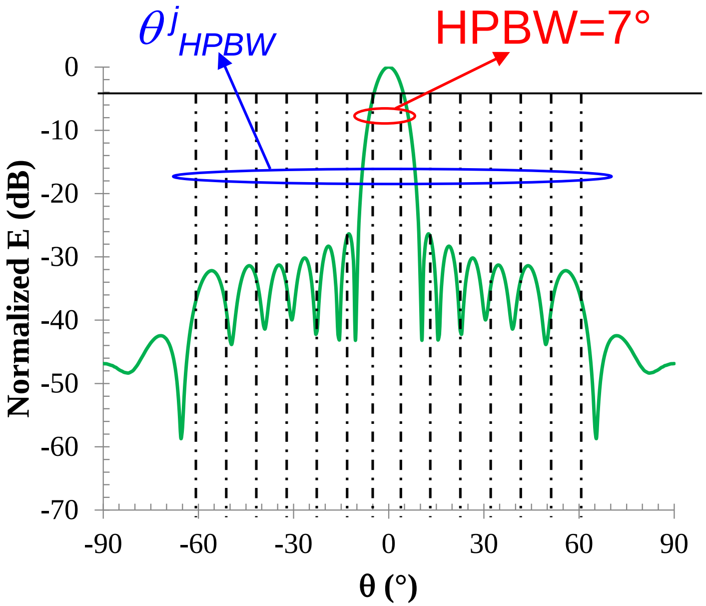
D. Masotti, R. Marchukov, V. Rizzoli, A. Costanzo, "Far-field Power Transmission by Exploiting Time-modulation in Linear Arrays," *IEEE WPTC 2015*, accepted for publication

Transfer of power to tags

- Once the tags position has been recordered:
- **2nd 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:

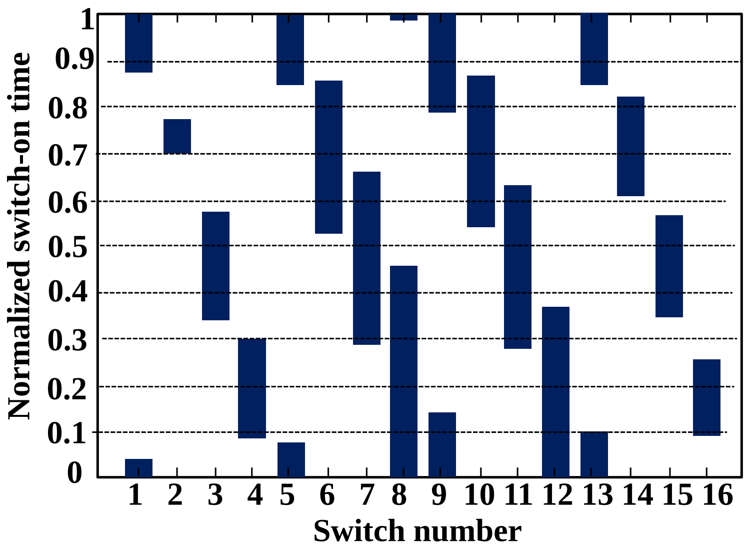
i. split the scanning region ($\theta \in [-60° \div 60°]$) into sectors of amplitude equal to the half power beam width (HPBW)

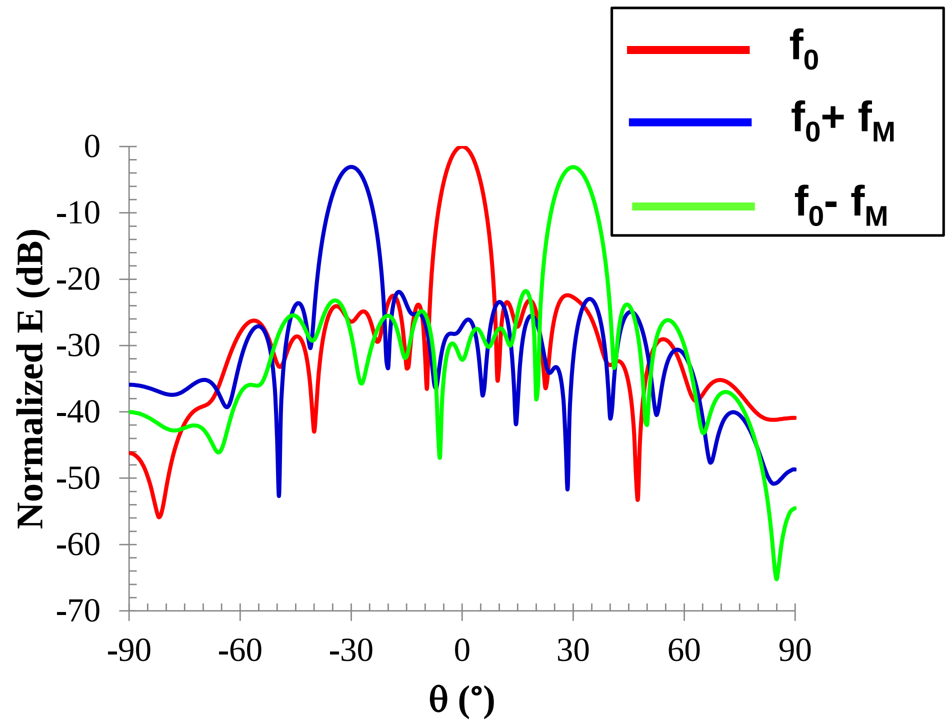
ii. for each θ_{peak} falling in the sector centered around θ_{HPBW}, the pre-loaded control sequence pointing the first harmonic to the θ_{HPBW} direction is used



Transfer of power to tags

- Case 1: θ_{peak} falling into the sectors centered around θ_{HPBW} = -30°, 0°, 30°



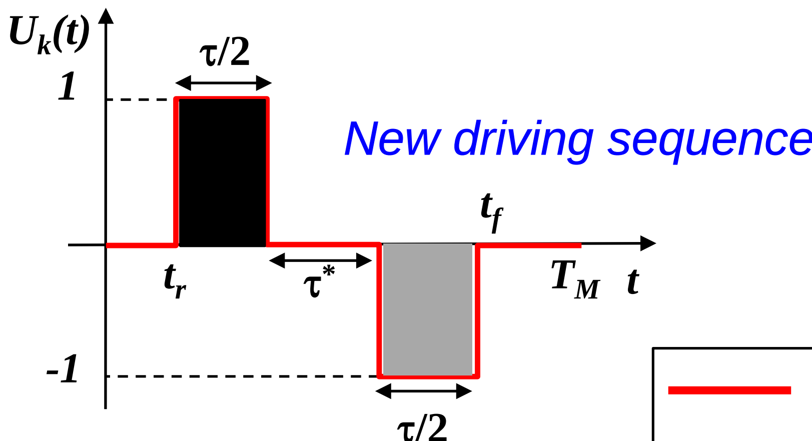


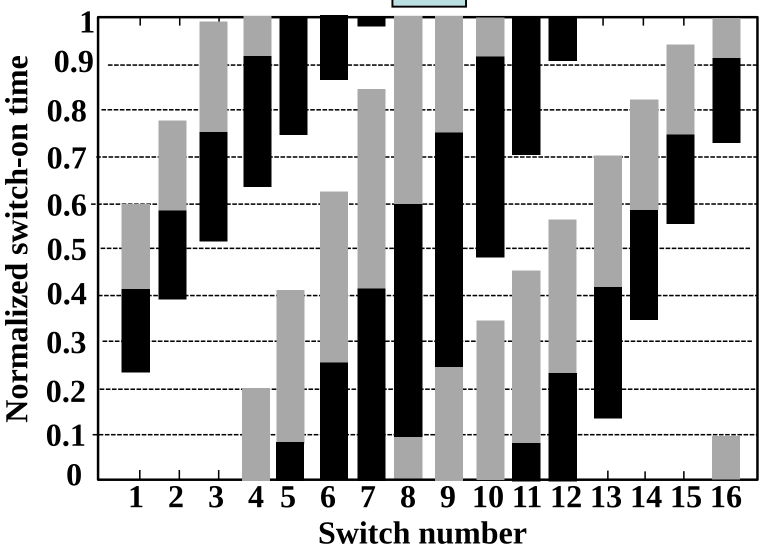
Simultaneous powering of the 3 tags

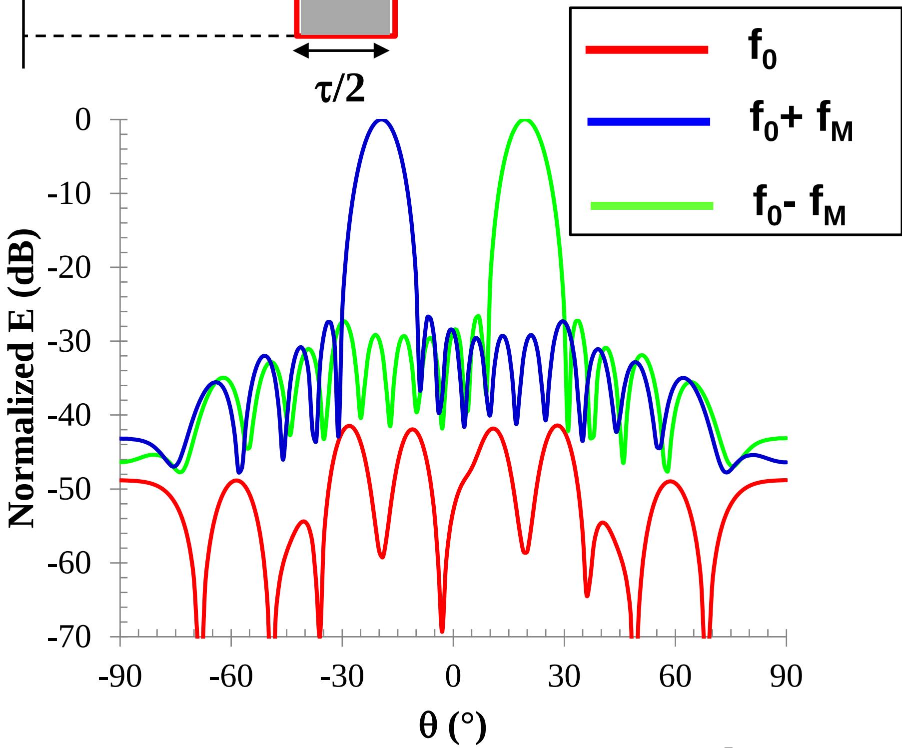
Transfer of power to tags

- Case 2: θ_{peak} falling into the sectors centered around θ_{HPBW} = -20°, 20°

Fundamental radiation is switched-off







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