



Radiation Pattern Shaping in Two-Element Time-Modulated Antenna Array

Grzegorz Bogdan

**Warsaw University of Technology
Institute of Radioelectronics**

24th International Travelling Summer School on Microwaves and Lightwaves
5 - 11 July, Copenhagen, Denmark



HUMAN CAPITAL
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN
SOCIAL FUND





<http://www.steelintheair.com/Cell-Phone-Tower.html>

$$\mathbf{E}_{\text{total}} = \mathbf{E}_{\text{element}} \times [\text{Array Factor}]$$

Array Factor depends on

- geometry of the array
- complex excitations (amplitude + **phase**)



- **Variable length of microstrip line**

- Low cost
- Fast switching (PIN or Schottky diodes)
- **Poor resolution** of phase-shift

- **Ferroelectric based phase-shifters**

- Permittivity controlled with electric field
- Wavelength and phase velocity are changing
- **High control voltages** (above 100V)

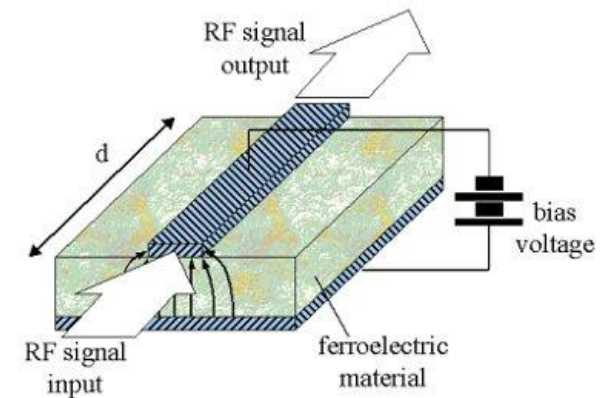
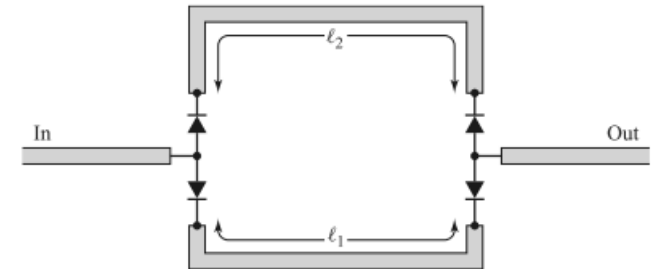
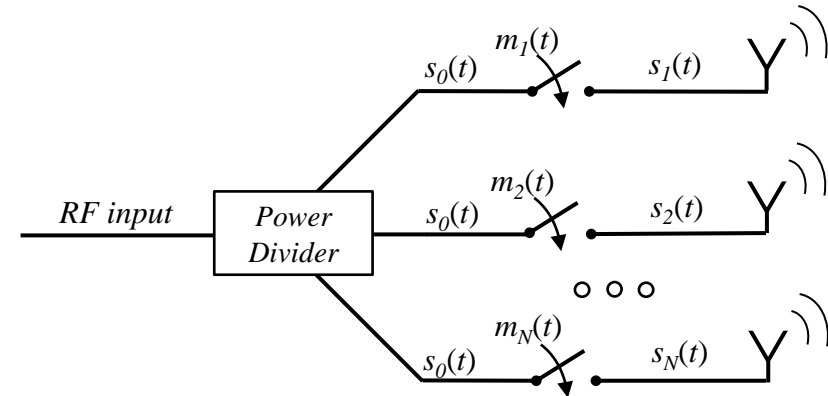


Figure 4: A structure of a ferroelectric-microstrip-based phase shifter. De Flavis *et al.* 1997

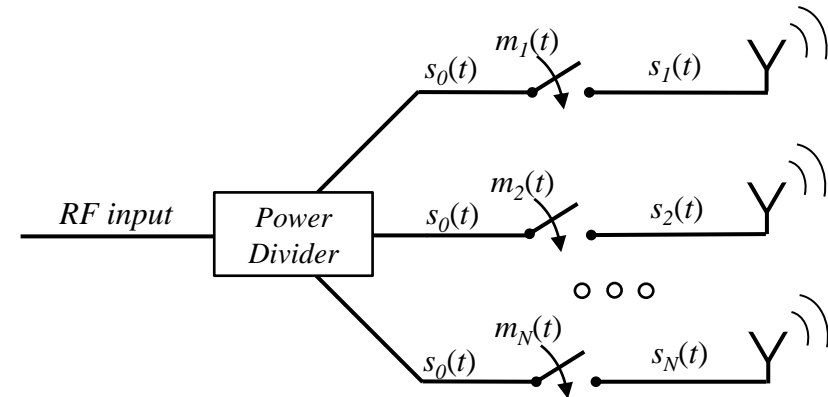
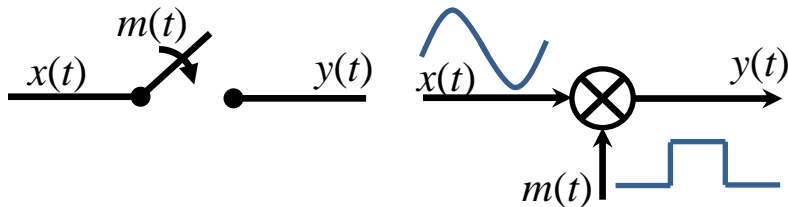
Microwave switches are turning ON and OFF
each of the antenna array elements



Microwave switches are turning ON and OFF each of the antenna array elements

Switching is periodical

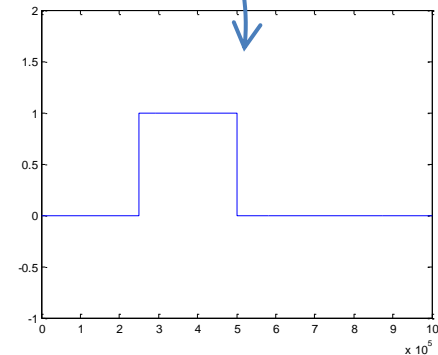
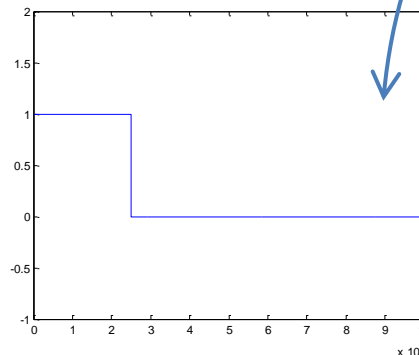
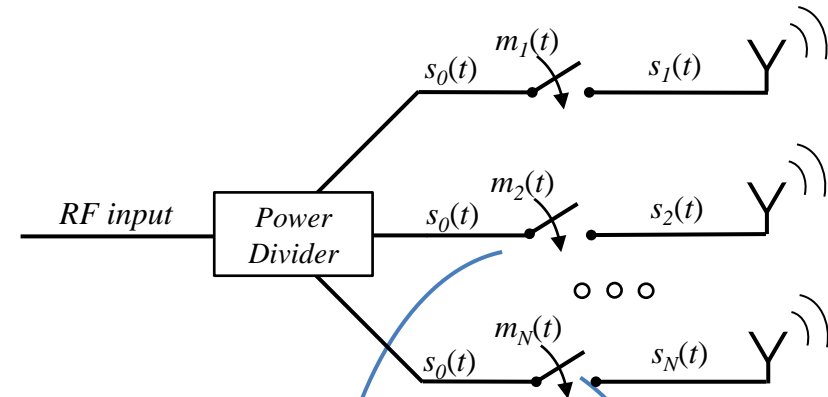
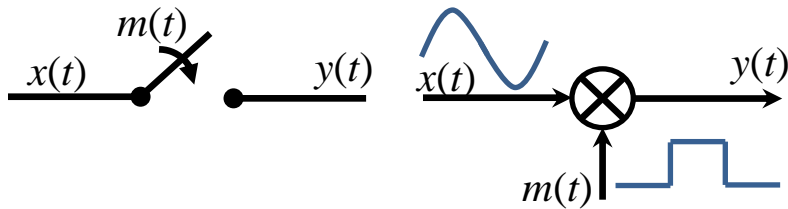
Time-modulation is based on switching
The Fourier Spectrum of $y(t)$ is the Fourier Spectrum of $m(t)$ shifted to the frequency of carrier $x(t)$



Microwave switches are turning ON and OFF each of the antenna array elements

Switching is periodical

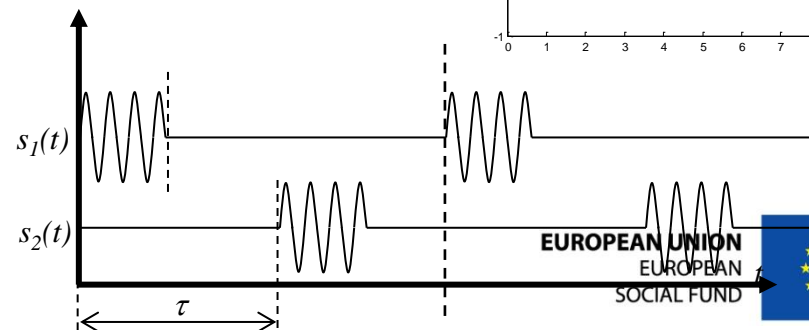
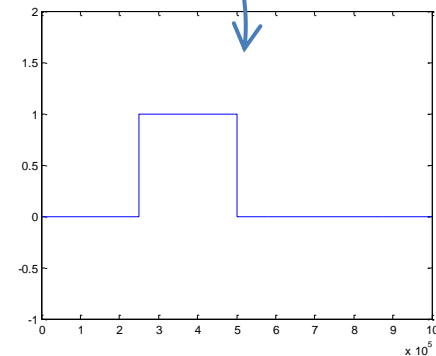
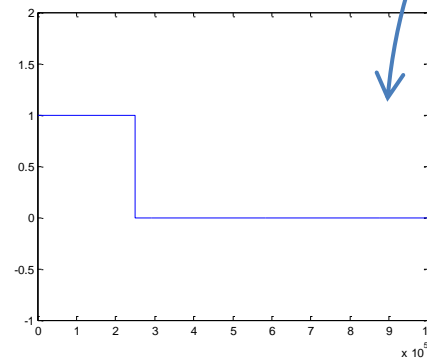
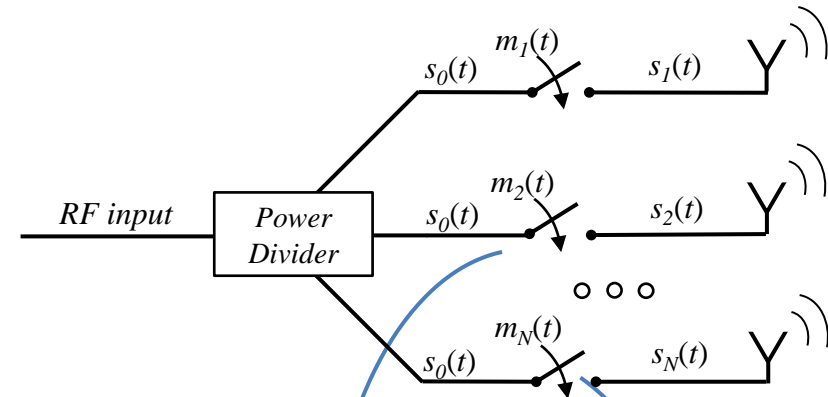
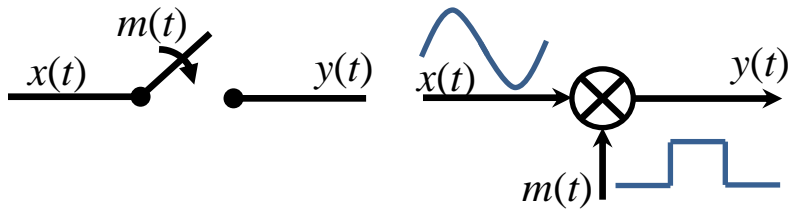
Time-modulation is based on switching
The Fourier Spectrum of $y(t)$ is the Fourier Spectrum of $m(t)$ shifted to the frequency of carrier $x(t)$



Microwave switches are turning ON and OFF each of the antenna array elements

Switching is periodical

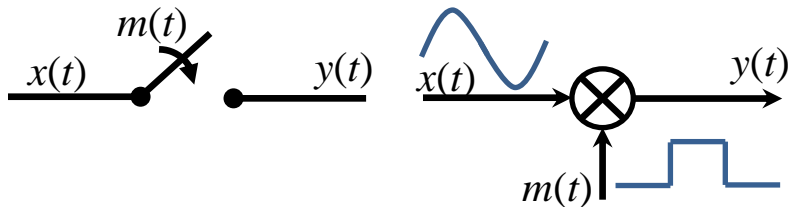
Time-modulation is based on switching
The Fourier Spectrum of $y(t)$ is the Fourier Spectrum of $m(t)$ shifted to the frequency of carrier $x(t)$



Microwave switches are turning ON and OFF each of the antenna array elements

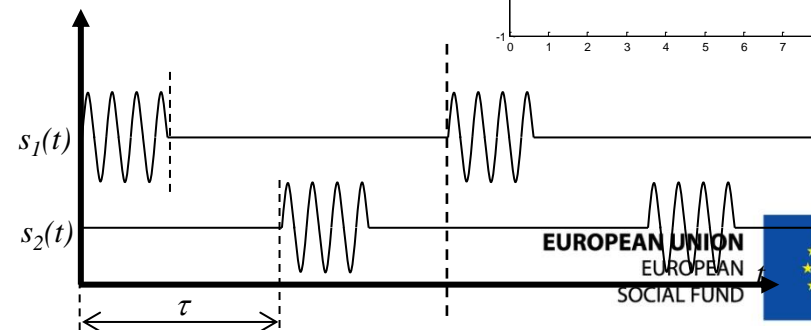
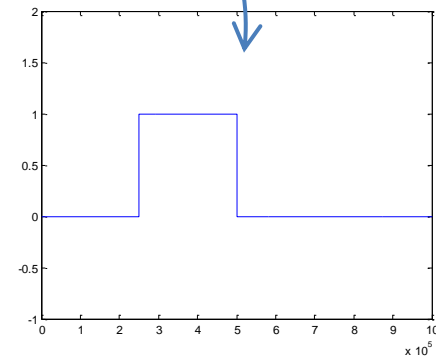
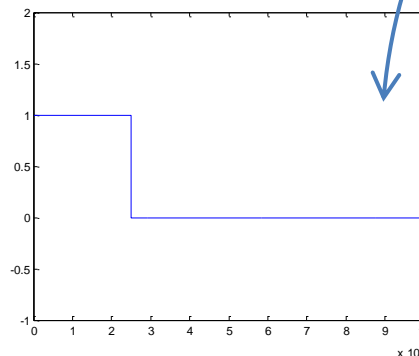
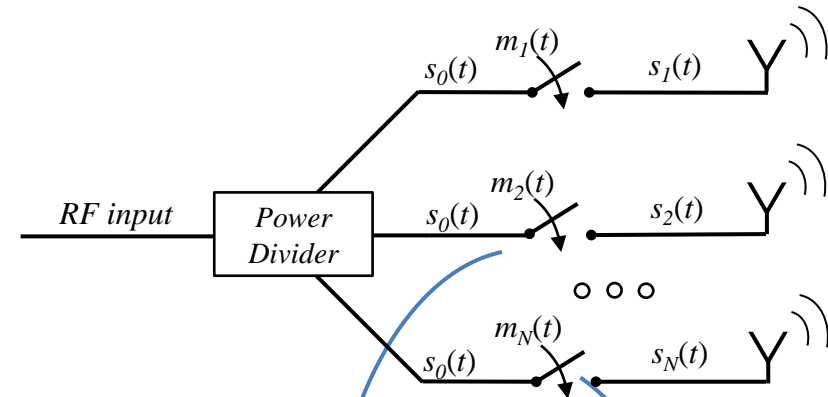
Switching is periodical

Time-modulation is based on switching
The Fourier Spectrum of $y(t)$ is the Fourier Spectrum of $m(t)$ shifted to the frequency of carrier $x(t)$



Duty cycle: 25%

Variable time-delay for ON state
 from $\tau = 0.25T_p$ to $\tau = 0.75T_p$



EUROPEAN UNION
EUROPEAN
SOCIAL FUND





$$m_n(t) = m_0(t - \tau_{delay})$$

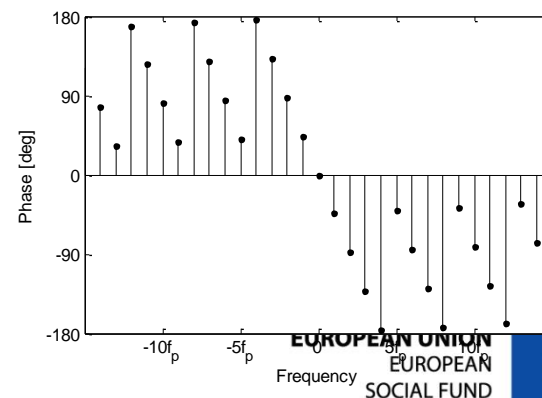
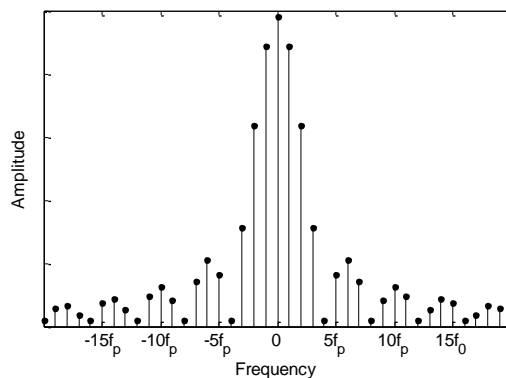
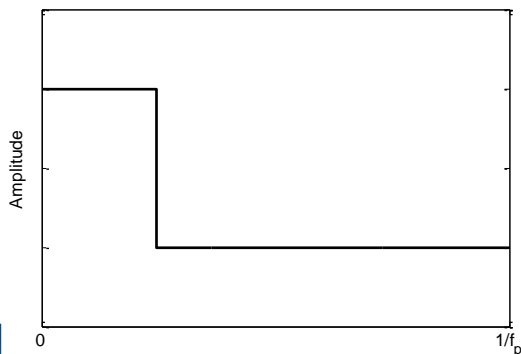
Fourier Transform

$$M_n[h] = M_0[h] e^{-j2\pi f_p h \tau_{n, delay}}$$

Discrete set of **complex amplitudes** called Fourier series coefficients

Phase-shift in frequency domain can be obtained by means of **time-delay** in time domain

$$\Delta\varphi_h = -2\pi f_p h \tau_{delay}$$



EUROPEAN UNION
EUROPEAN
SOCIAL FUND



Spectrum analysis of modulating signal $m(t)$

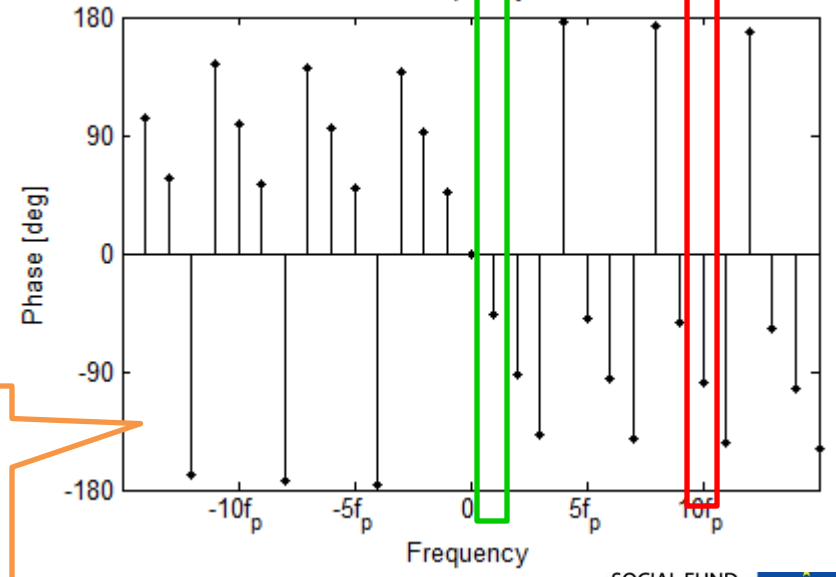
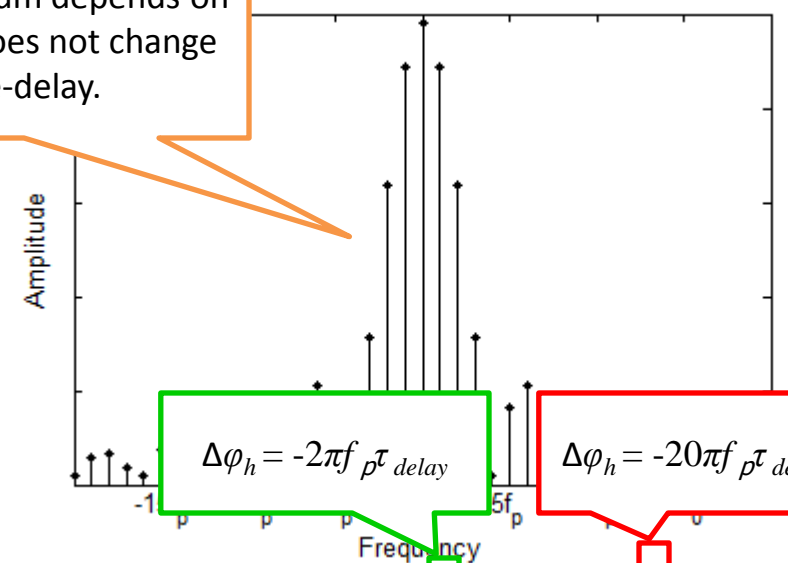
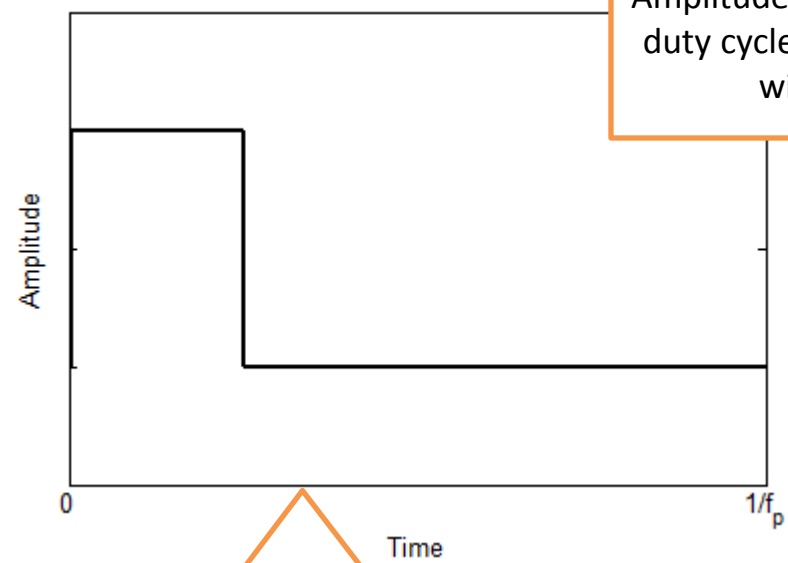


Amplitude Spectrum depends on duty cycle and does not change with time-delay.

Periodical rectangular waveform with variable time-delay

Phase-shift is proportional to coefficient (harmonic) number and applied time-delay

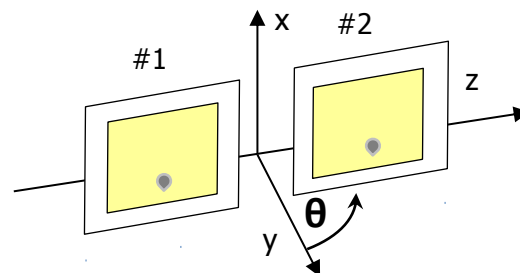
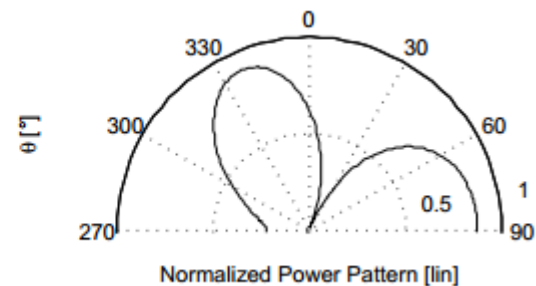
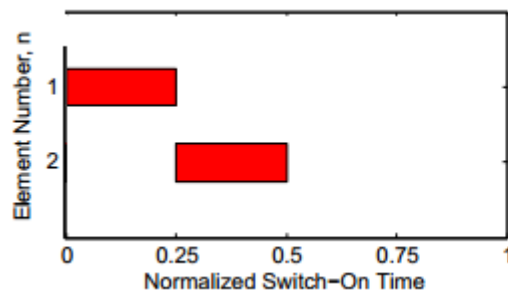
$$\Delta\varphi_h = -2\pi f_p h \tau_{delay}$$



Simulations at the first harmonic



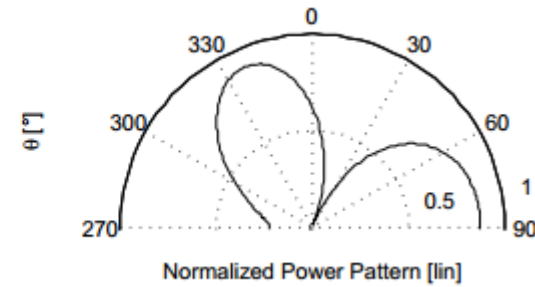
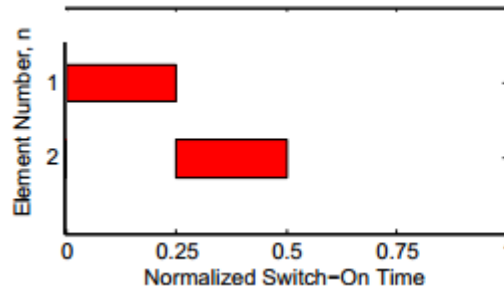
$$\tau_{delay} = 0.25T_p$$
$$\Delta\varphi = 90^\circ$$



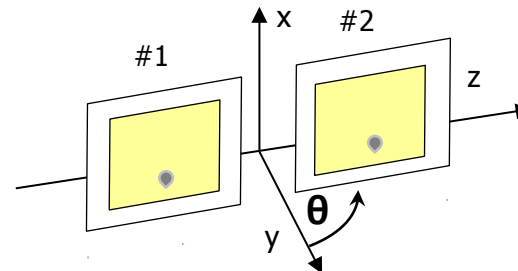
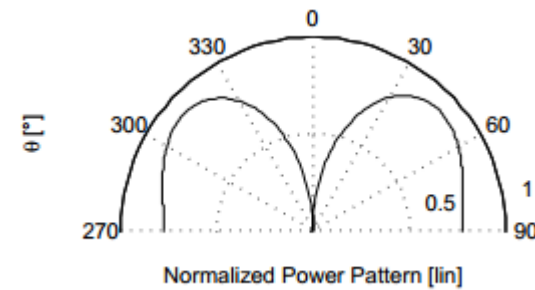
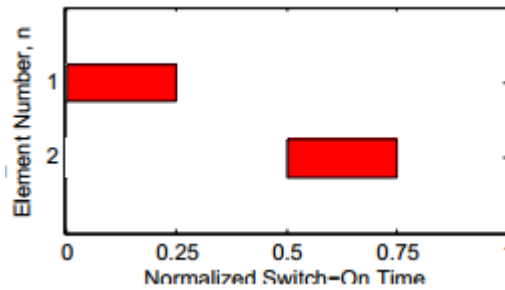
Simulations at the first harmonic



$$\tau_{delay} = 0.25T_p$$
$$\Delta\varphi = 90^\circ$$

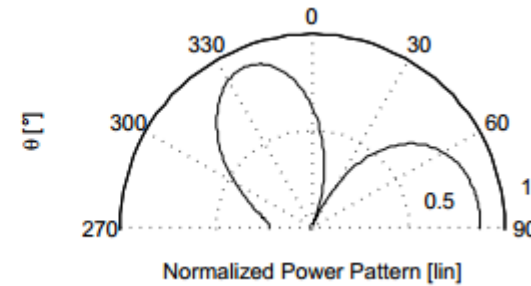
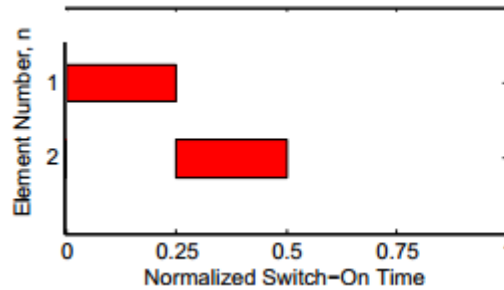


$$\tau_{delay} = 0.50T_p$$
$$\Delta\varphi = 180^\circ$$



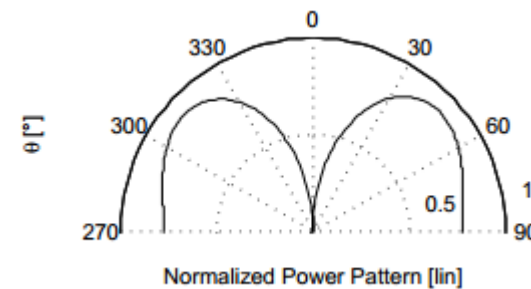
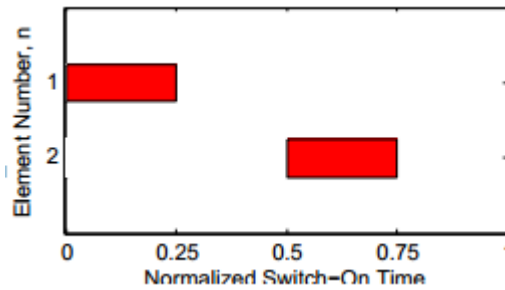
$$\tau_{delay} = 0.25T_p$$

$$\Delta\varphi = 90^\circ$$



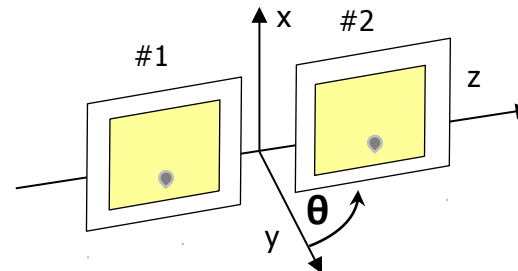
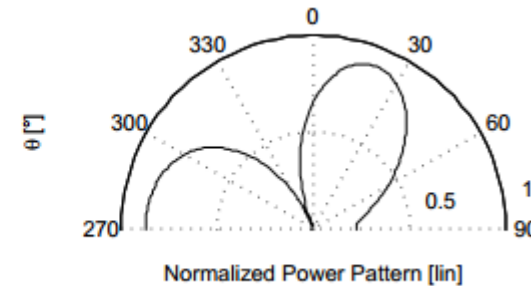
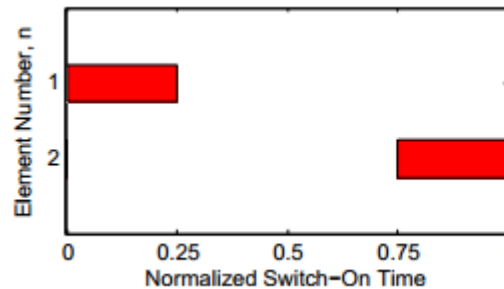
$$\tau_{delay} = 0.50T_p$$

$$\Delta\varphi = 180^\circ$$

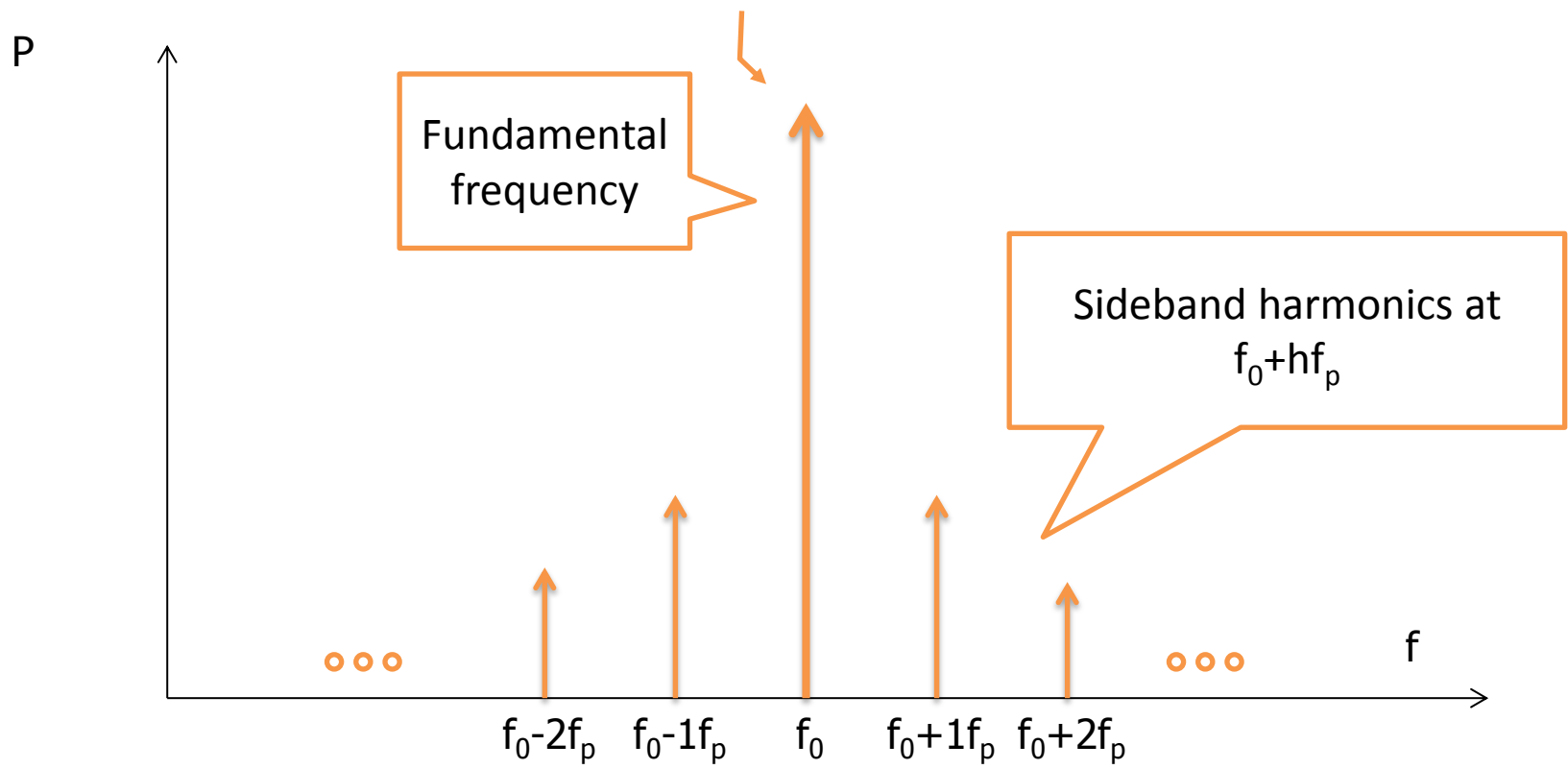


$$\tau_{delay} = 0.75T_p$$

$$\Delta\varphi = 270^\circ$$



$$E = j\eta \frac{I_0}{2\pi r} \sum_{h=-\infty}^{\infty} e^{-j(h\omega_p + \omega)t} \sum_{n=1}^N c_{nh} e^{j(n-1)kd \cos \theta}$$

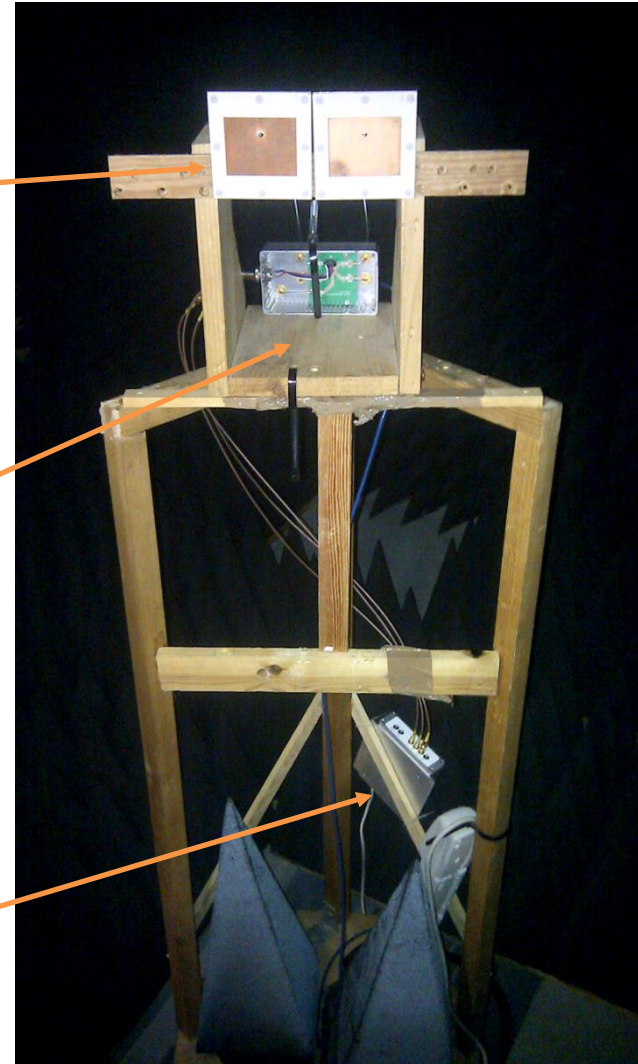


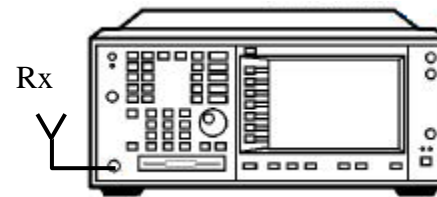
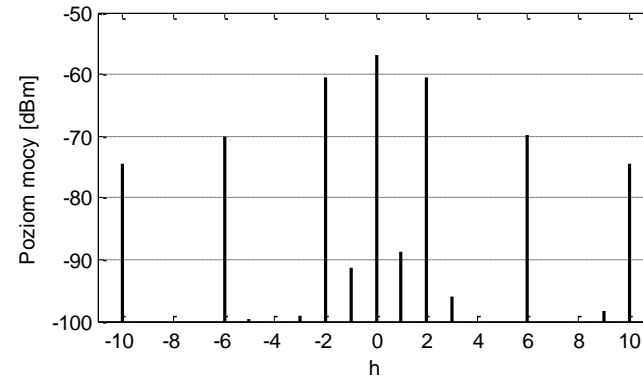
Separation between harmonic components depends on switching period, e.g.: for RF switch with rise time **40 ns** the separation is around **5 MHz**

Two 2.4 GHz patch
antennas

Modulator
(SP4T RF switch)

Control unit
(rise time < 1 ns)



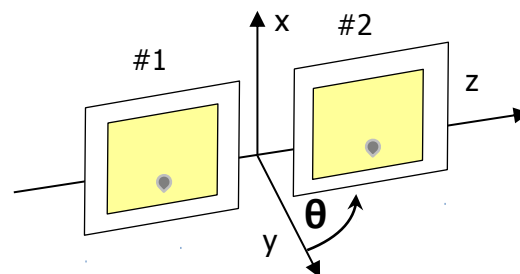
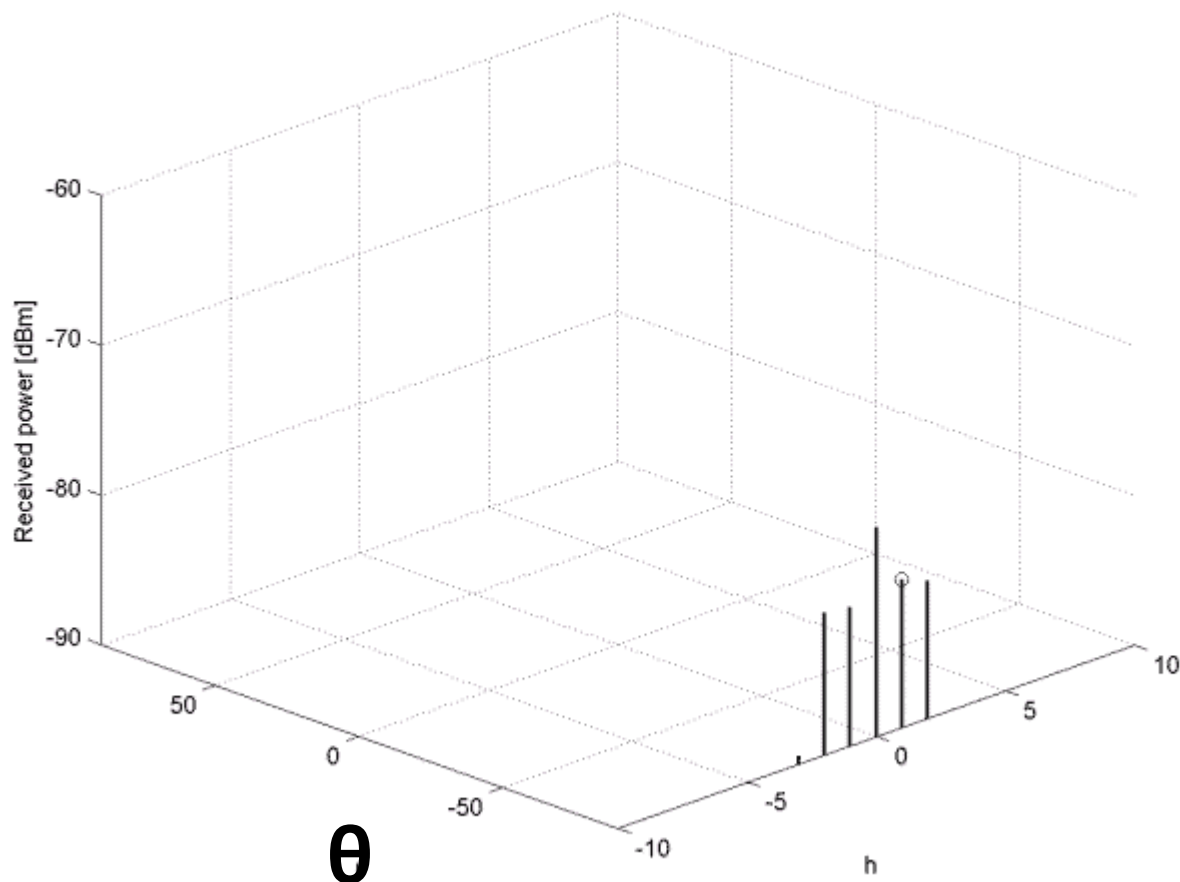


VNA used as a spectrum analyzer

$$f_0 = 2.45 \text{ GHz}$$

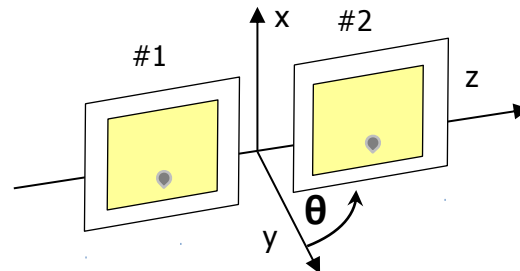
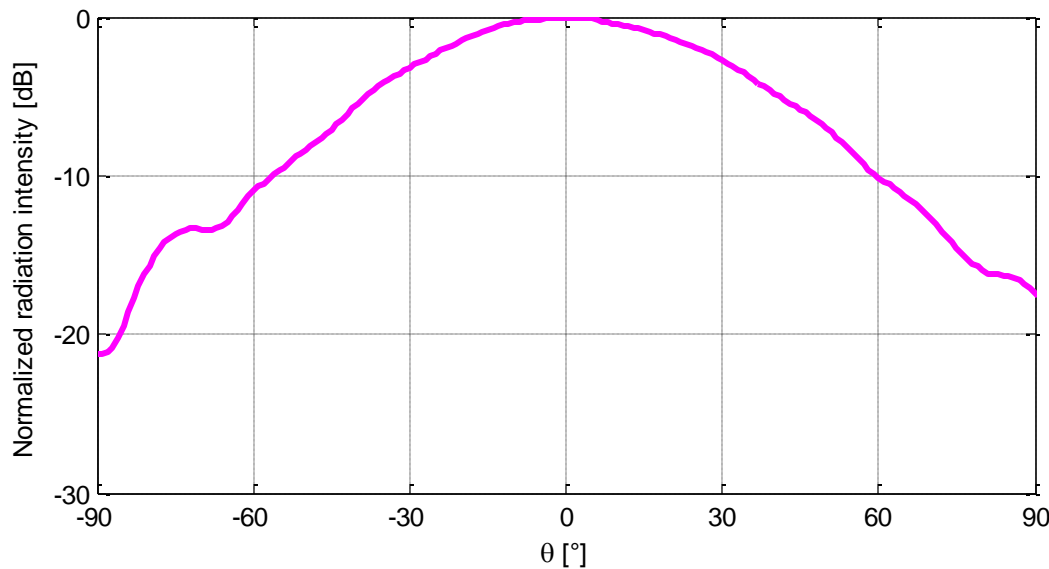
$$f_p = 10 \text{ kHz } (T_p = 100 \mu\text{s})$$

$$\text{BW} = 100 \text{ Hz}$$

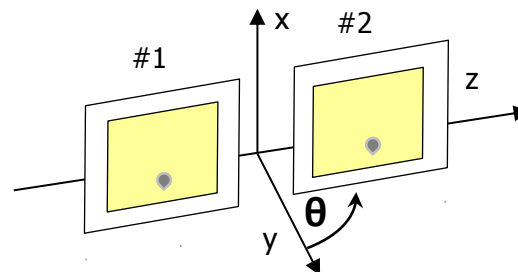
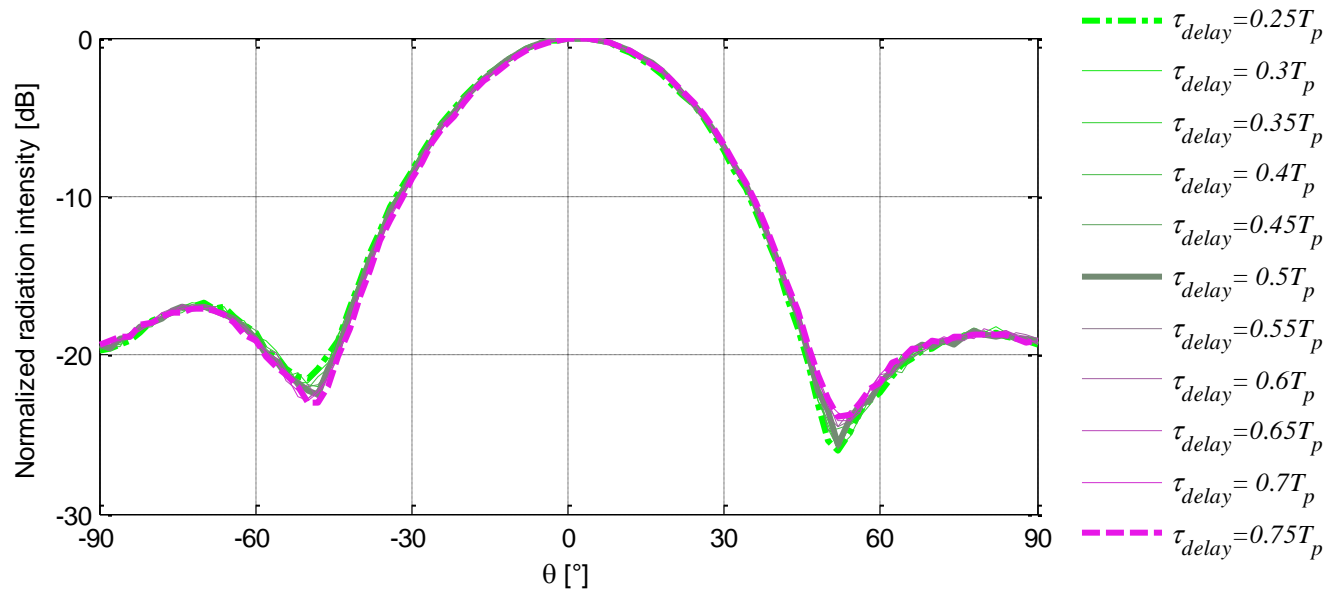




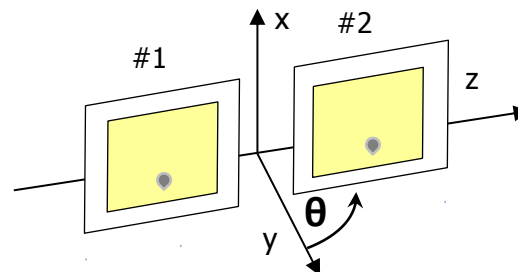
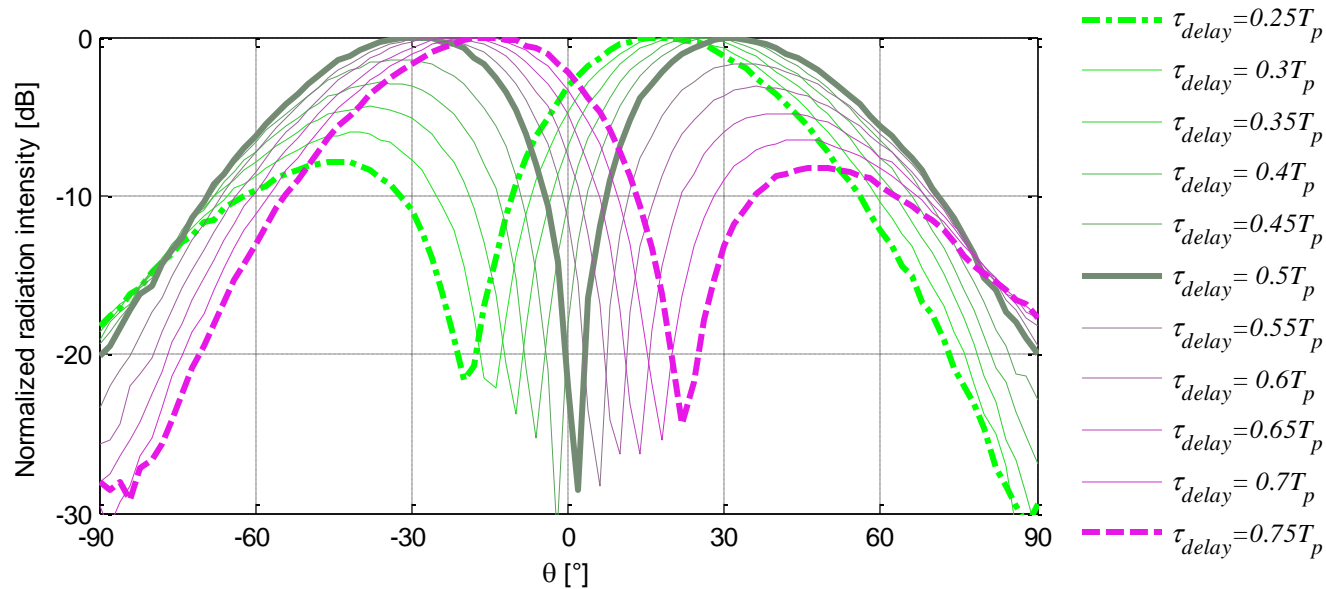
Radiation pattern of isolated element without time-modulation



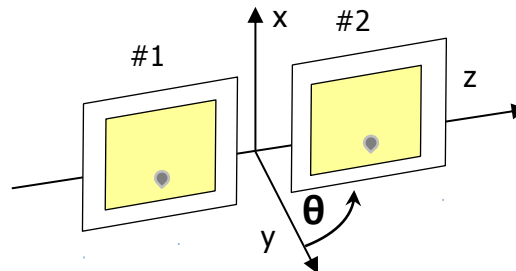
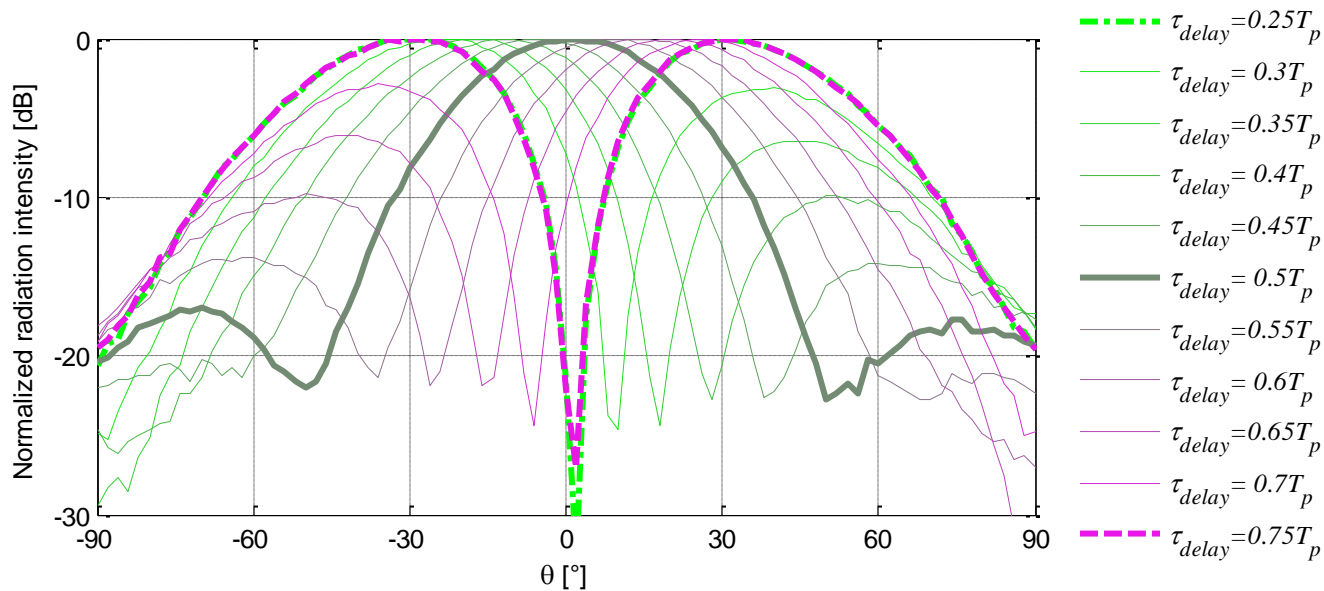
Time-delay (or phase-shift) do not affect radiation pattern at the fundamental frequency



Null can be controlled in range of angles from -22° to 22°

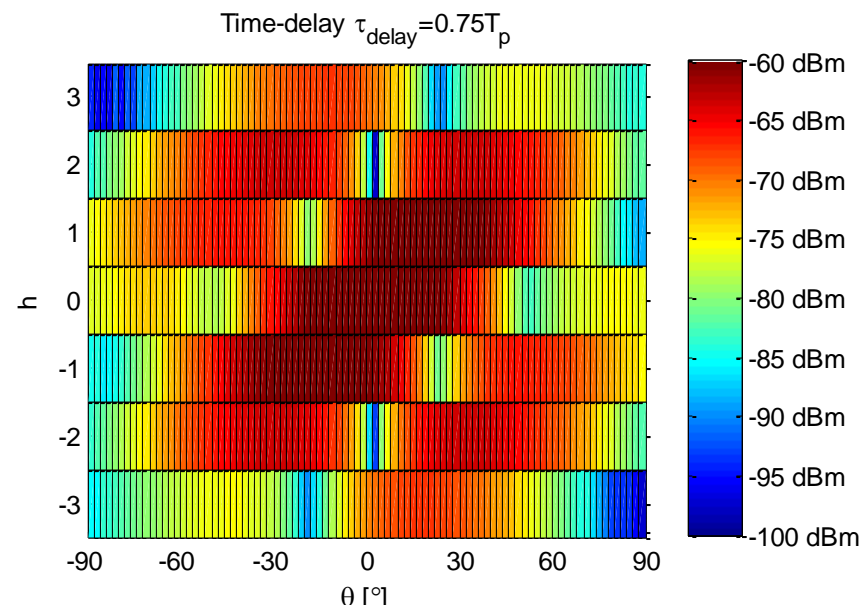


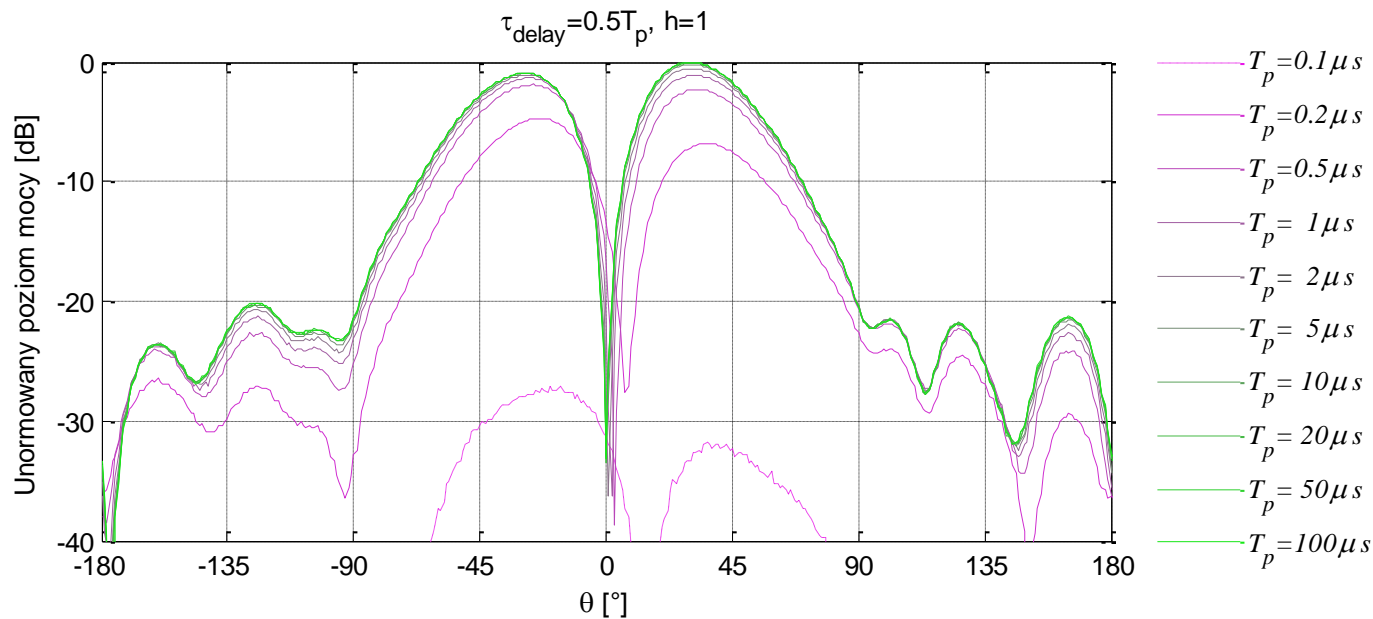
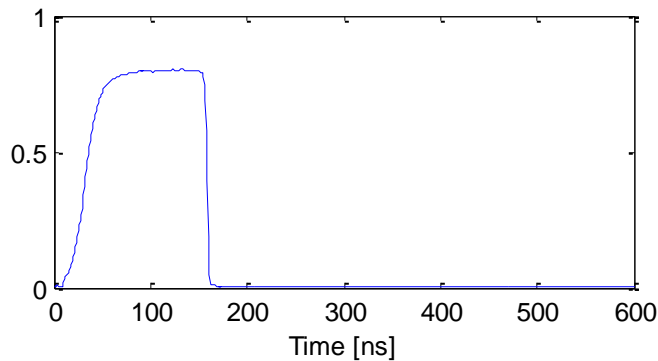
Null can be controlled in range of angles from -50° to 50°

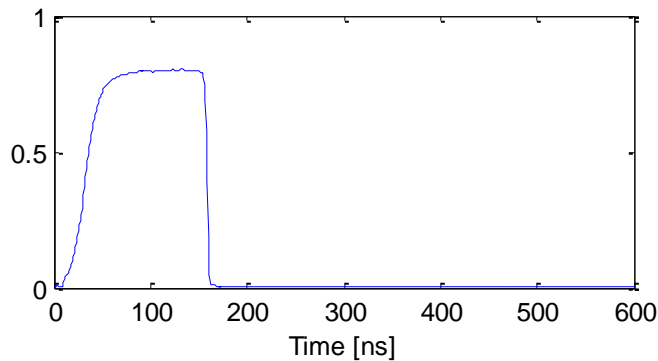


Multiple nulls directed simultaneously in different directions

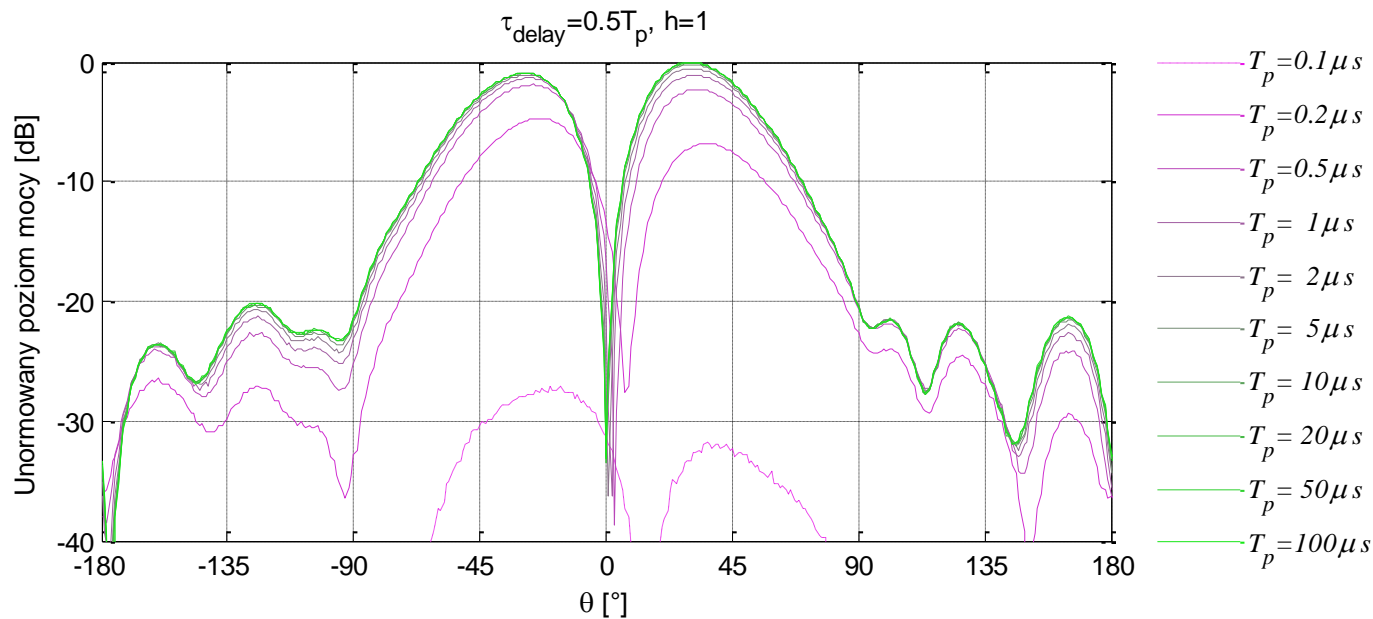
(MIMO, OFDM, adaptive interference cancelation,
direction finding)



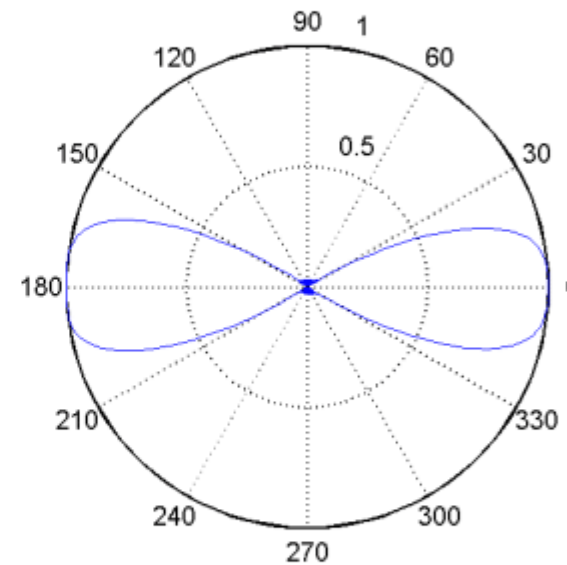
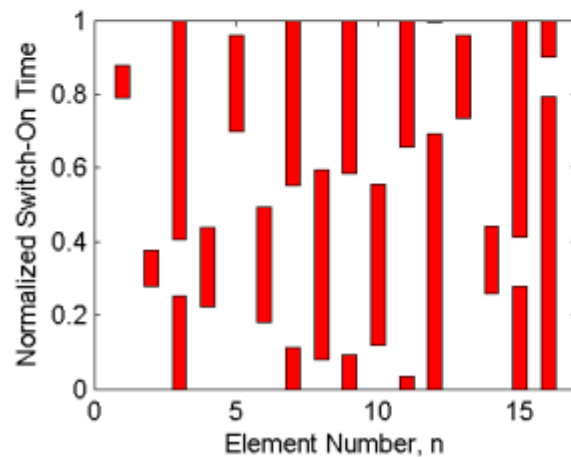
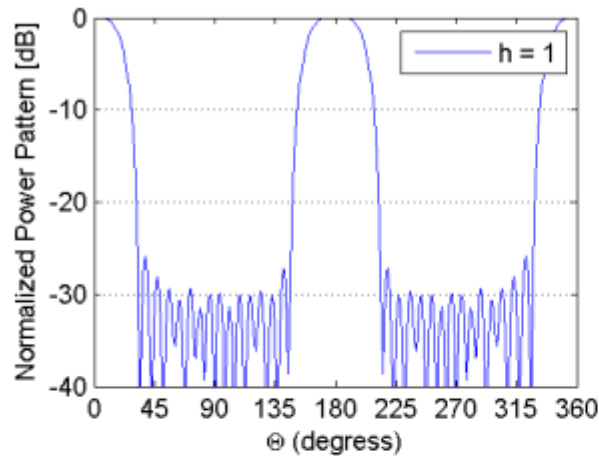




Maximum
bandwidth:
2 MHz



Time Modulated Linear Array with beam-steering (increased size to 8 or 16 elements)





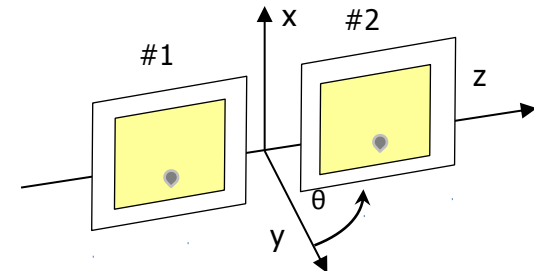
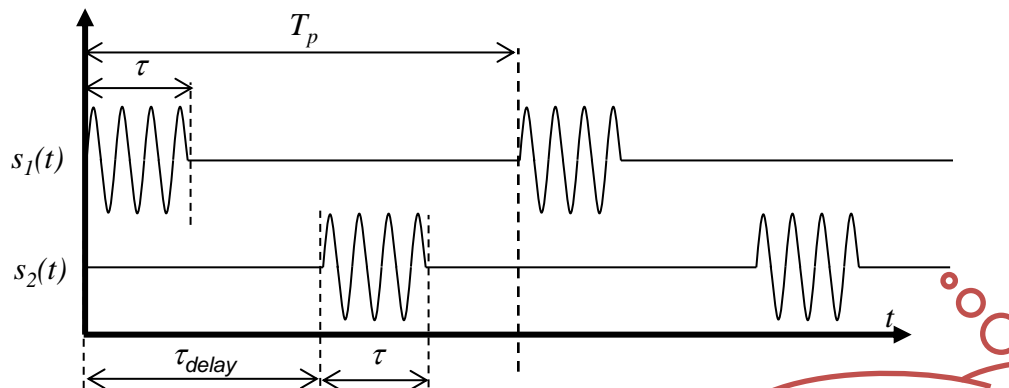
Thank you for your attention

Grzegorz Bogdan

**Warsaw University of Technology
Institute of Radioelectronics**

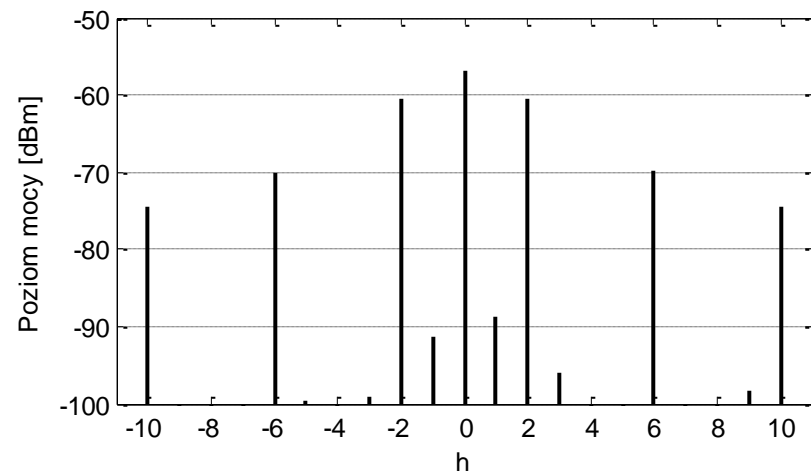
**24th International Travelling Summer School on Microwaves and Lightwaves
5 - 11 July, Copenhagen, Denmark**





Opóźnienie czasowe zmienia fazę na harmonicznych wypromieniowanych przez antenę #2.

Sygnal odebrany jest superpozycją sygnałów nadanych a jego widmo zależy od punktu obserwacji (kątown azymutu oraz elewacji)



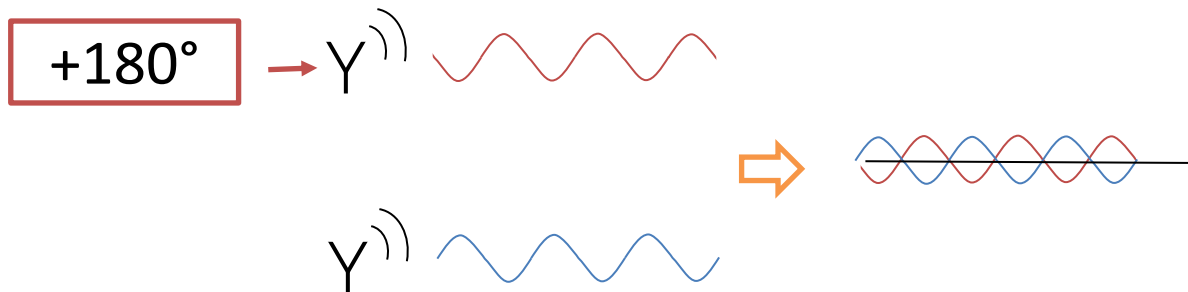
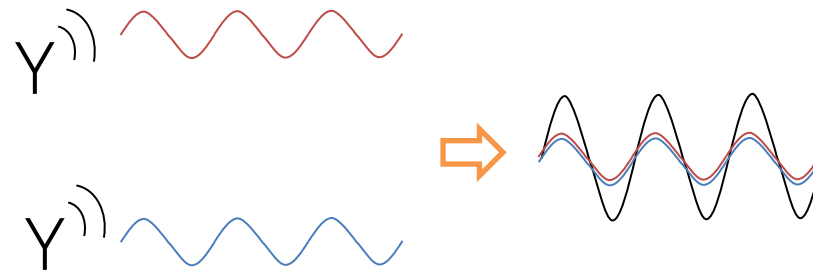
Kształtowanie charakterystyki kierunkowej



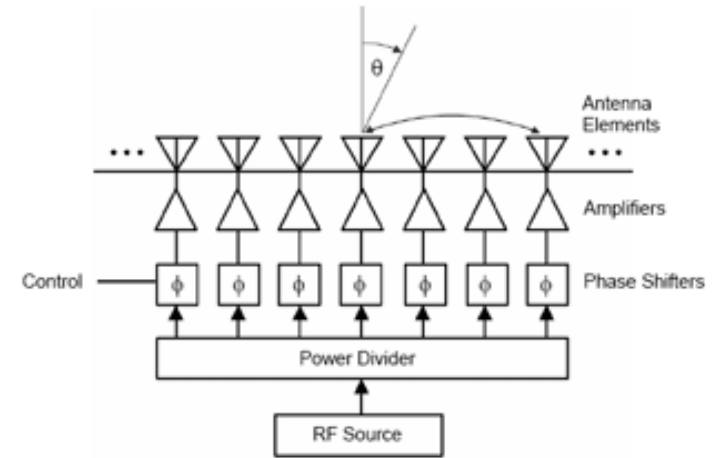
Wsparcie inicjatyw Politechniki Warszawskiej w kształceniu i doskonaleniu kadr w zakresie innowacyjnych technik teleinformatycznych



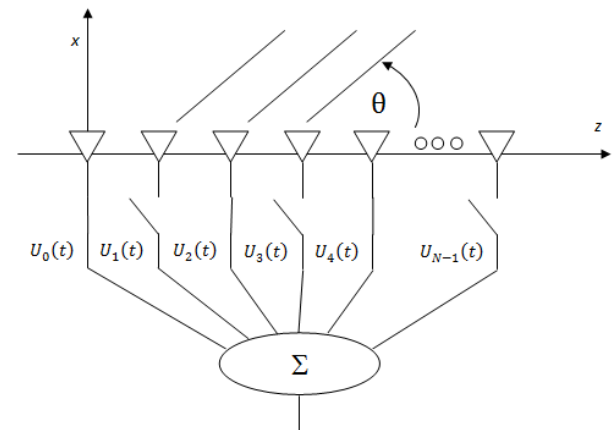
Kształtowanie charakterystyki promieniowania szyku antenowego możliwe jest dzięki interferencji (konstruktywnej lub destruktywnej) fal wypromieniowanych przez poszczególne elementy szyku.



Typowo, zmianę kształtu charakterystyki kierunkowej szyku antenowego („skanowanie”) uzyskać można stosując koncepcję **szyku fazowanego**.



Modulowane czasowo szyki antenowe, zamiast **przesuwników fazy** oraz **regulowanych wzmacniaczy**, wykorzystują **przełączniki sygnału w.cz.**



Zalety:

- zmniejszenie kosztów produkcji
- łatwa integracja w krzemie

Szanse:

- stworzenie taniego modułu kształtowania wiązki szyku antenowego



Wsparcie inicjatyw Politechniki Warszawskiej
w kształceniu i doskonaleniu kadr w zakresie
innowacyjnych technik teleinformatycznych



HUMAN CAPITAL
NATIONAL COHESION STRATEGY

EUROPEAN UNION
EUROPEAN
SOCIAL FUND



$$E(\theta) = f_e(\theta) \sum_{n=0}^{N-1} a_n e^{j(\omega t + nkd \cos \theta)}$$

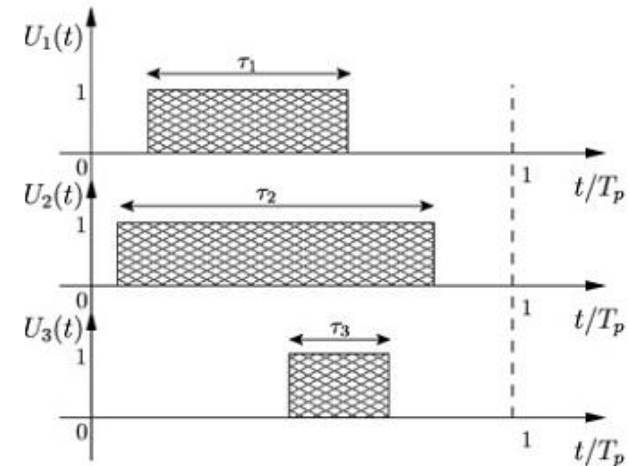
$$E(\theta) = f_e(\theta) \sum_{n=0}^{N-1} U_n(t) e^{j(\omega t + nkd \cos \theta)}$$

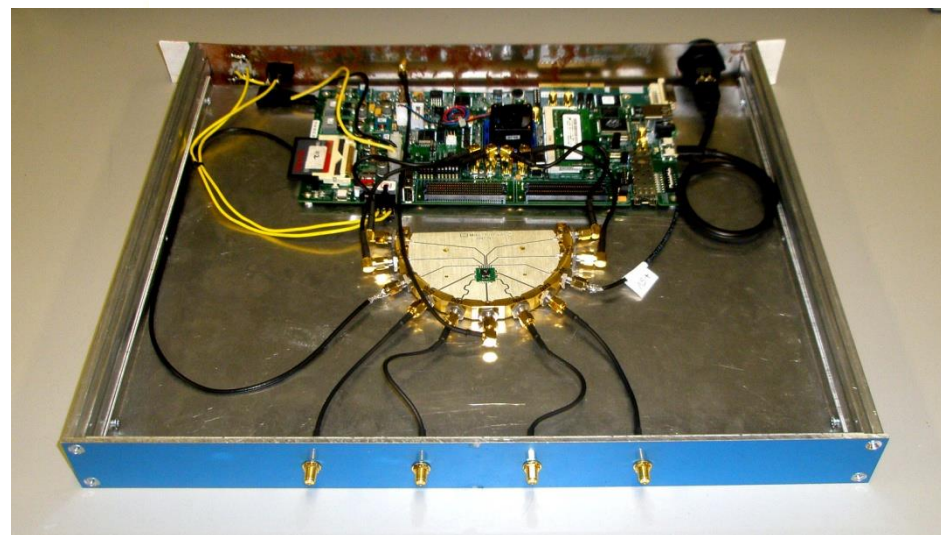
$U_n(t)$ może zostać zapisany w postaci wykładniczego szeregu Fouriera.

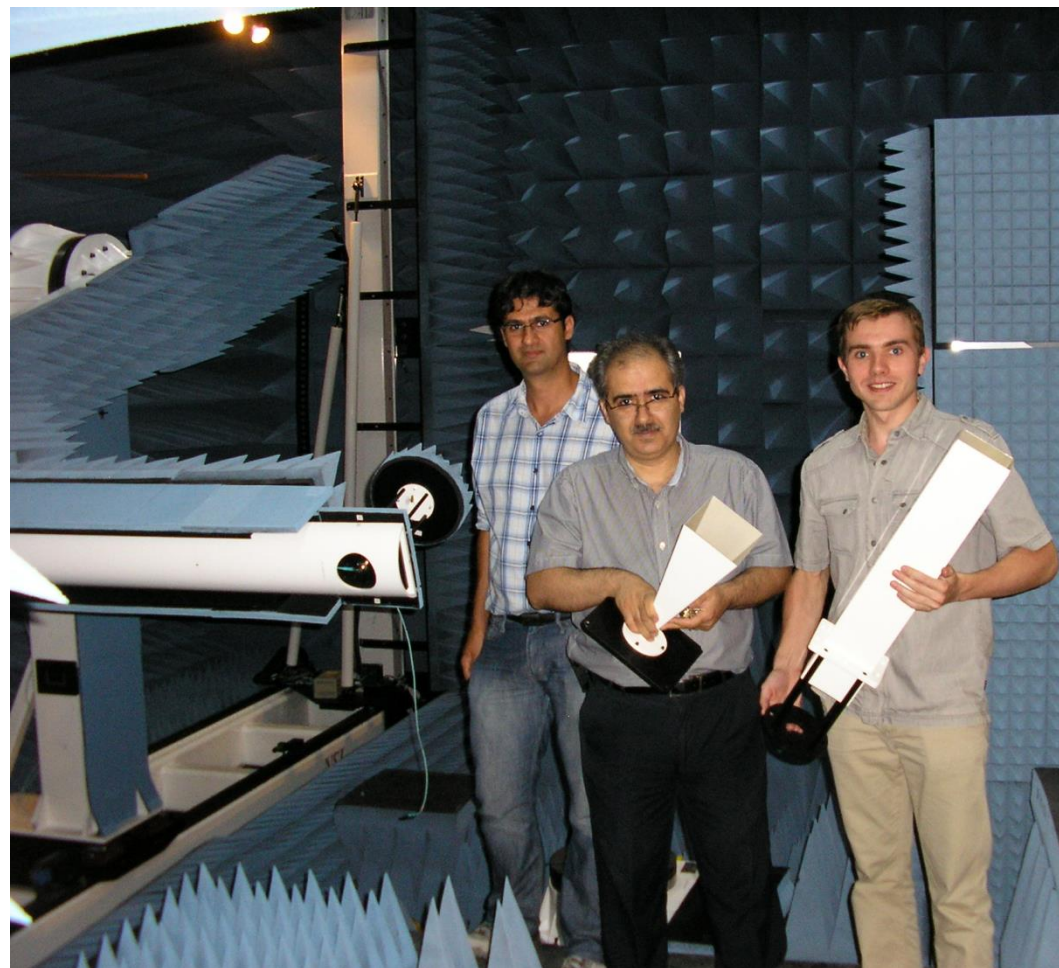
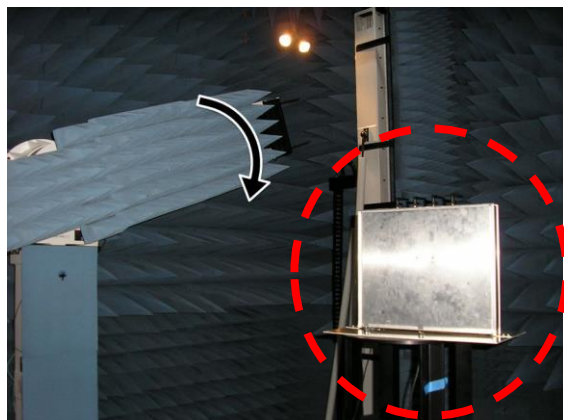
$$U_n(t) = \sum_{h \in \mathbb{Z}} u_{nh} e^{jh\omega_p t}, \quad \omega_p = \frac{2\pi}{T_p}$$

$$u_{nh} = \frac{1}{T_p} \int_0^{T_p} U_n(t) e^{-jh\omega_p t} dt$$

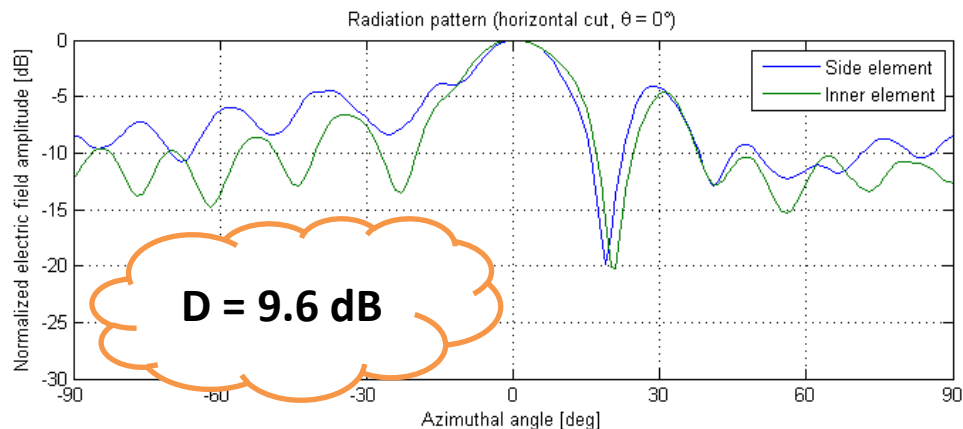
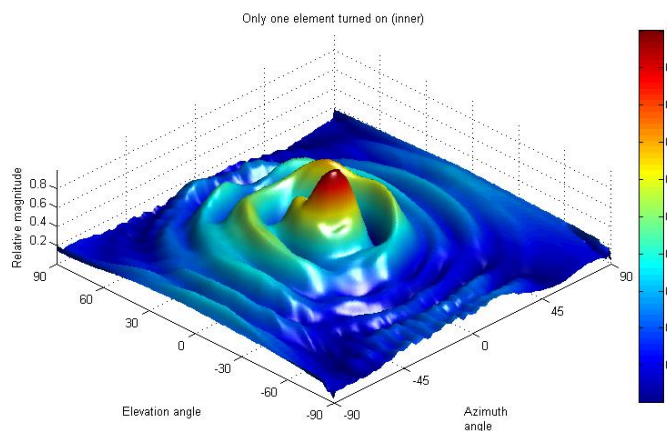
$$E(\theta) = f_e(\theta) \sum_{h \in \mathbb{Z}} e^{j(\omega + h\omega_p)t} \sum_{n=0}^{N-1} u_{nh} e^{jnkd \cos \theta}$$



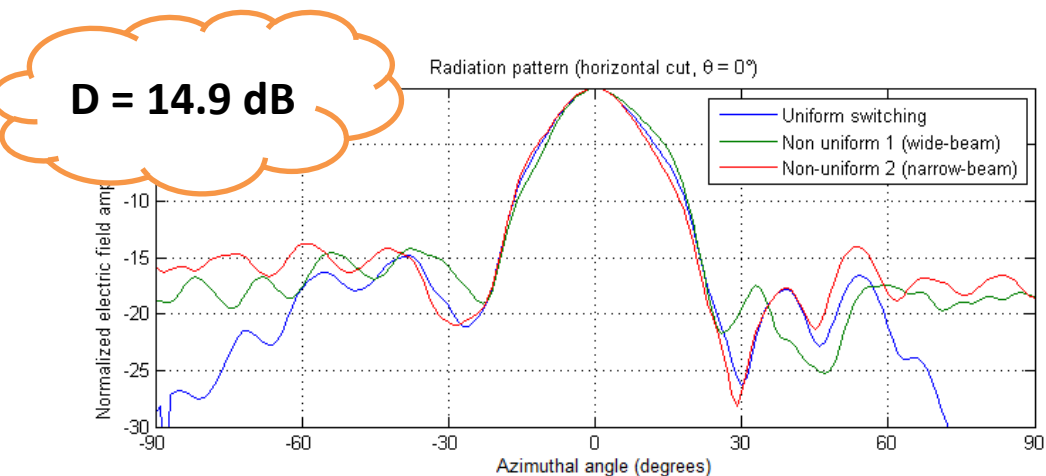
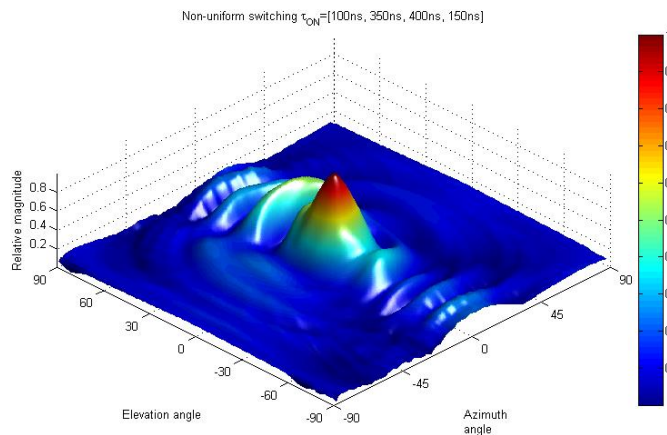




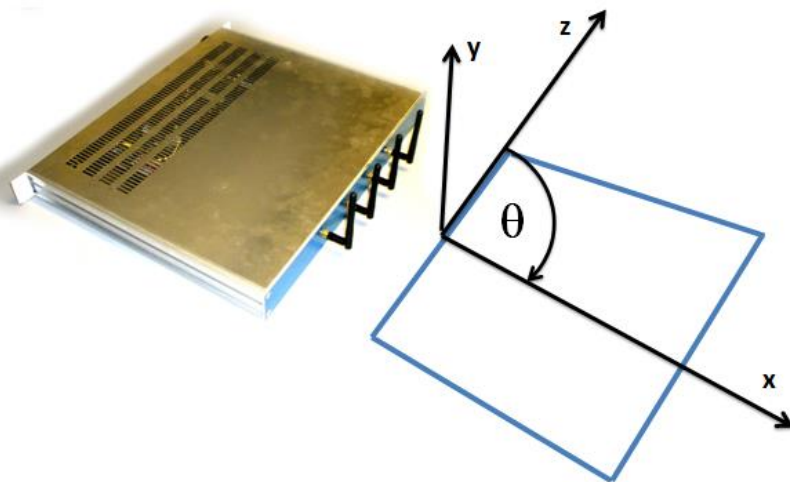
Rys. Komora bezdechowa, University of Waterloo, Kanada (źródło: materiały własne / ciars.uwaterloo.ca)



Rys A. Unormowana charakterystyka promieniowania pojedynczego elementu (wewnętrzny / zewnętrzny element)

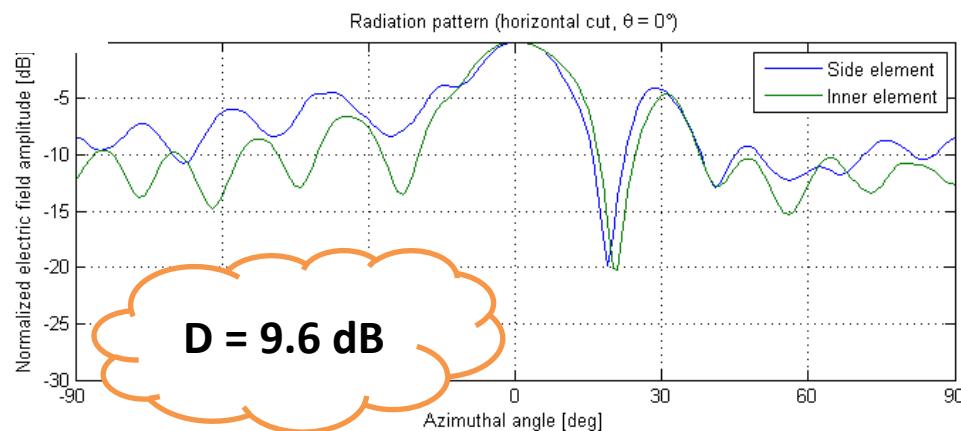
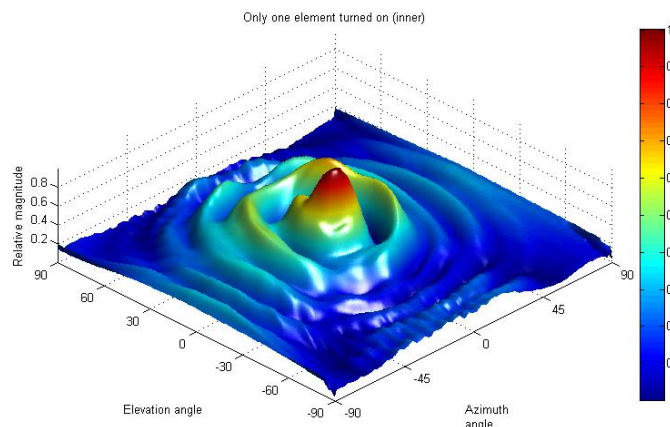


Rys B. Unormowana charakterystyka promieniowania szyku antenowego dla różnego rodzaju przełączania



Wstępne założenie o wszekierunkowości pojedynczego dipola w płaszczyźnie H okazało się błędne.

Rozwiązanie: uwzględnienie zmierzonej charakterystyki elementu w symulacjach.



Rys A. Unormowana charakterystyka promieniowania pojedynczego elementu (wewnętrzny / zewnętrzny element)



$$E(\theta) = f_e(\theta) \sum_{h \in \mathbb{Z}} e^{j(\omega + h\omega_p)t} \sum_{n=0}^{N-1} u_{nh} e^{jnkd \cos \theta} \quad [1]$$

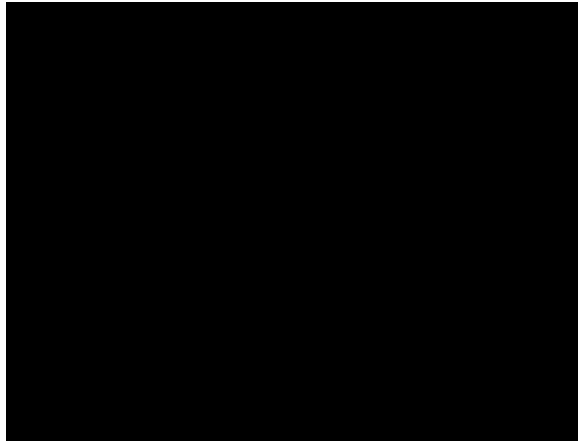
Nieskończona ilość
harmonicznych

Położenie harmoniczných
zależy od okresu modulacji
szyku antenowego $T_p = 2\pi/\omega_p$

[1] W. Kummer, A. Villeneuve, T. Fong, and F. Terrio, "Ultra-low side-lobes from time-modulated arrays" *Antennas and Propagation, IEEE Transactions on*, vol. 11, no. 6, pp. 633–639, 1963

Mechaniczne kształtowanie charakterystyki promieniowania

Szyk antenowy z rotorem
(Warszawa Okęcie)



Elektroniczne kształtowanie charakterystyki promieniowania

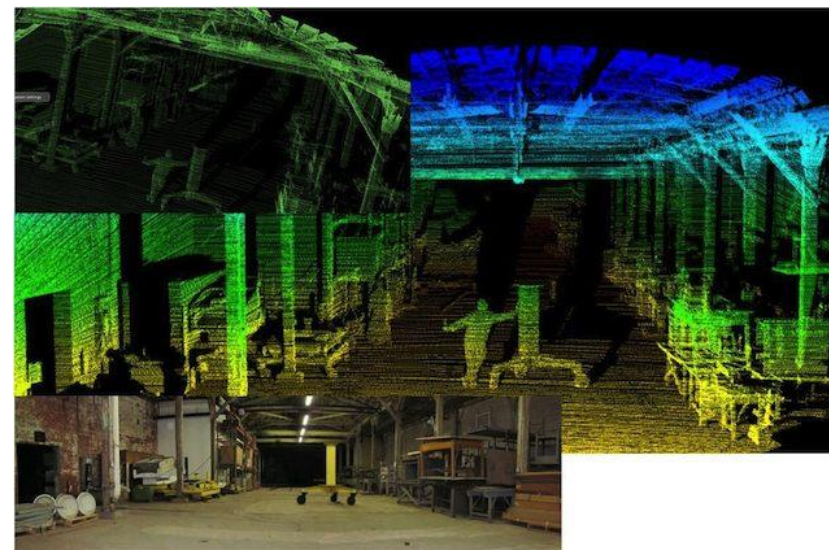
Fazowany szyk antenowy
(radar meteorologiczny, USA)



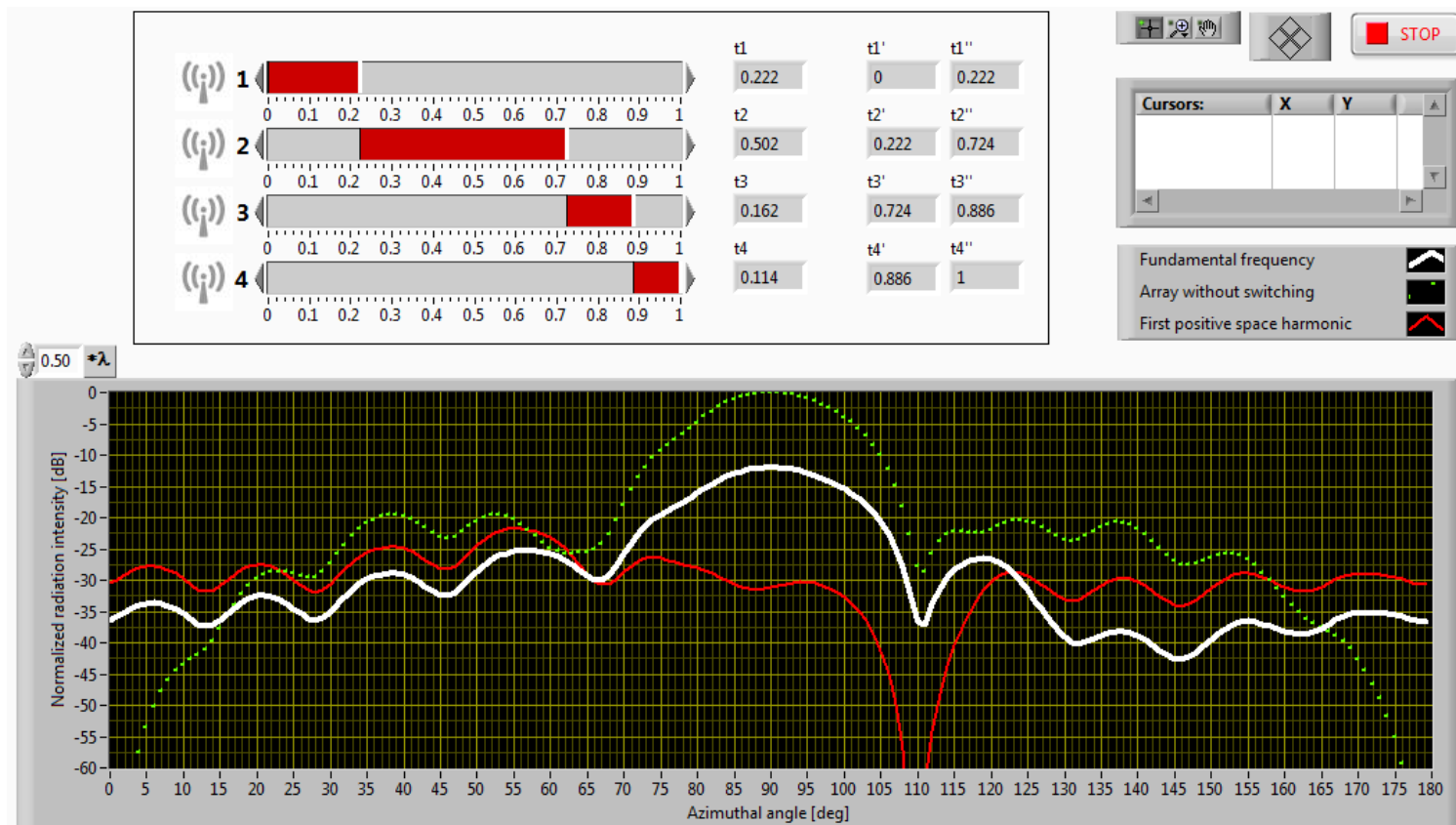
Szyk akustyczny (głośniki, mikrofony)

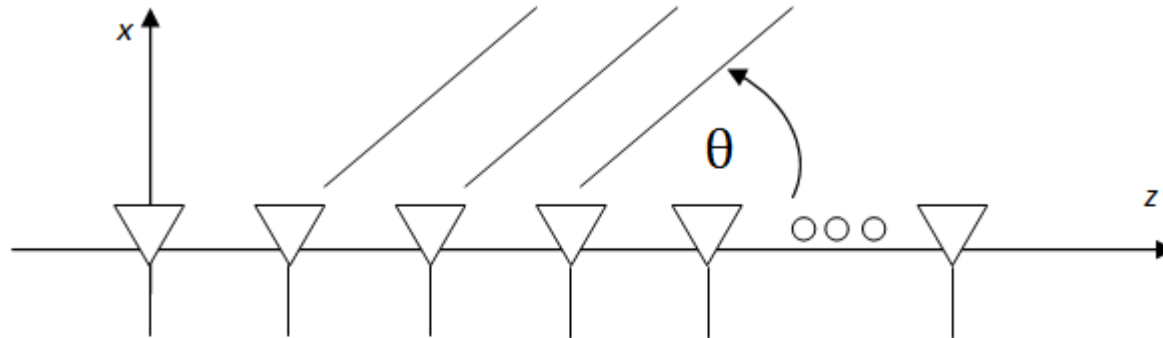


Szyk optyczny (przełączniki i multipleksery optyczne, radar optyczny)



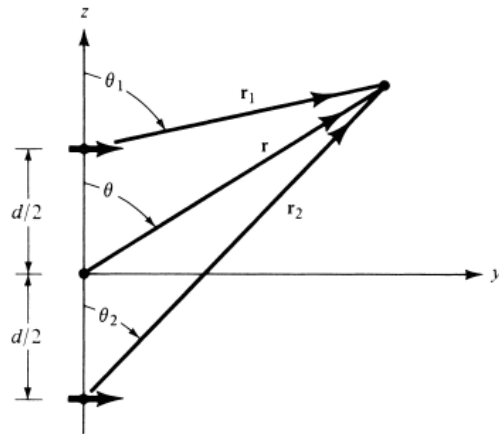
Adaptive nulling



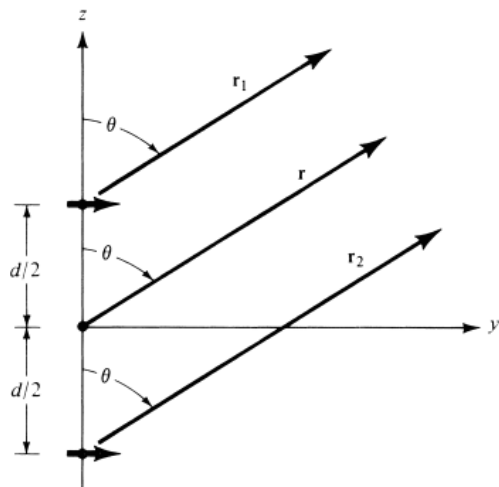


$$E(\theta) = f_e(\theta) \sum_{n=0}^{N-1} a_n e^{j(\omega t + nkd \cos \theta)}$$

a_n Zespólona amplituda pobudzenia n-tego elementu



(a) Two infinitesimal dipoles



(b) Far-field observations

Charakterystyka grupowa:

$$AF = \sum_{n=1}^N e^{j(n-1)(kd \cos \theta + \beta)}$$

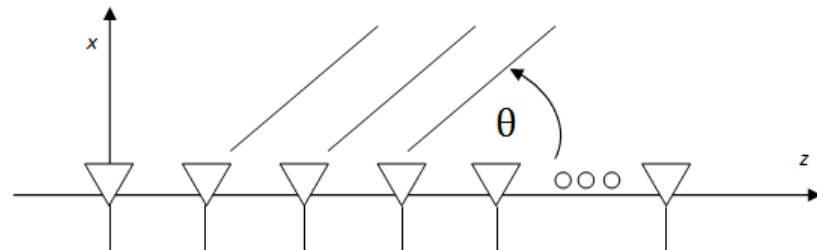
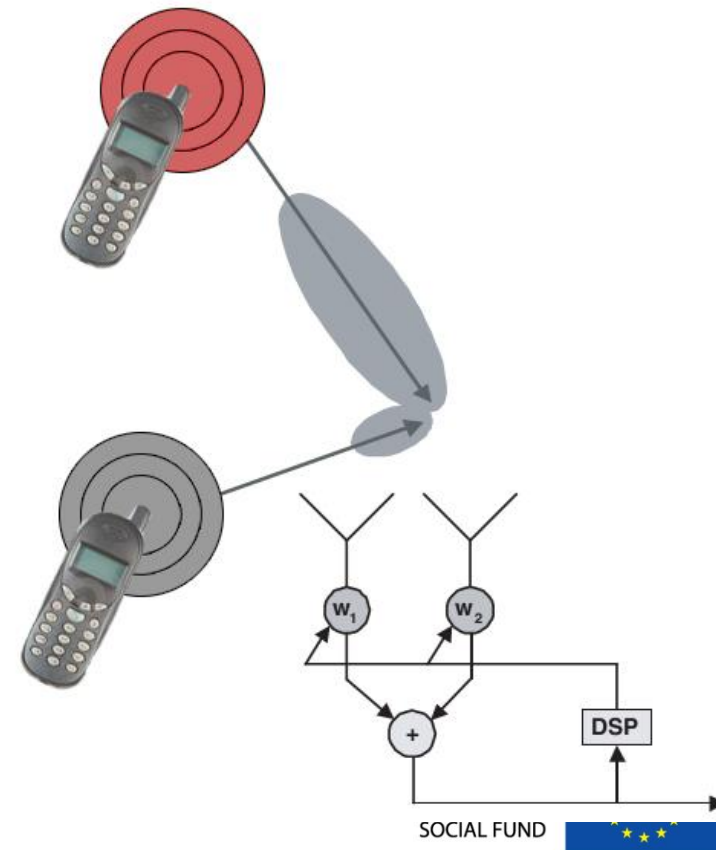


Figure 6.1 Geometry of a two-element array positioned along the z-axis

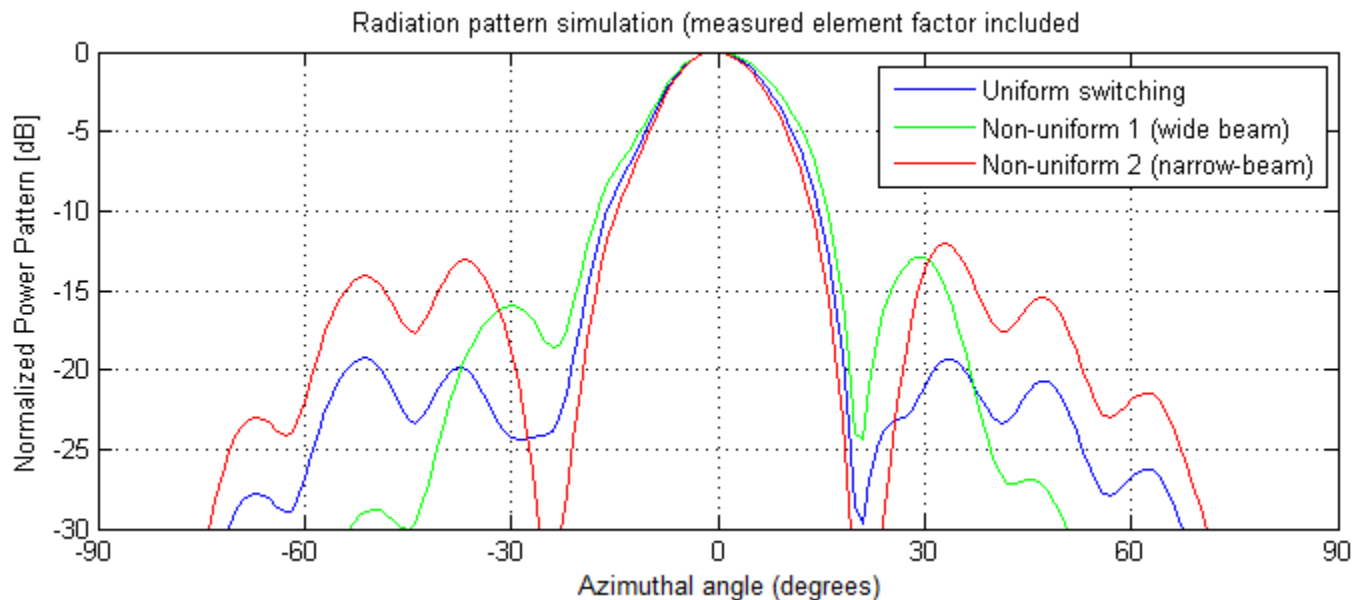
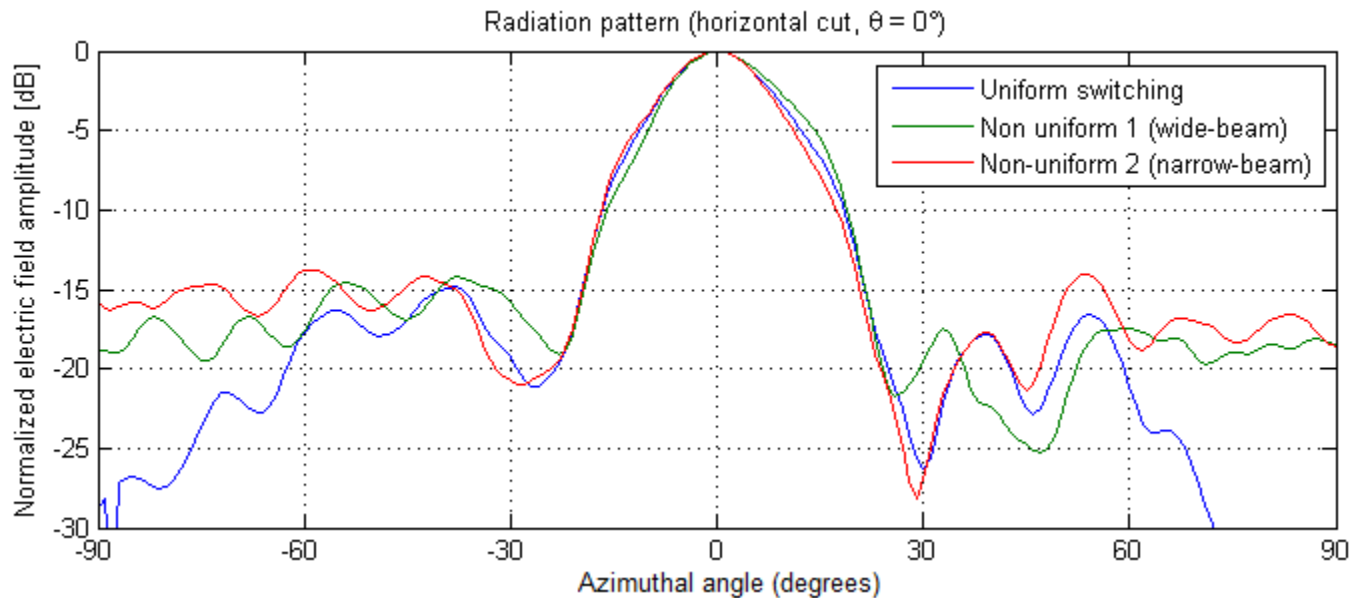
Inteligentna antena to system składający się z szyku antenowego oraz algorytmów cyfrowego przetwarzania sygnałów.

Podstawowe funkcje:

- estymacja lokalizacji pożądanego użytkownika oraz kierunku nadchodzenia zakłóceń
- kształtowanie wiązki szyku antenowego w celu zwiększenia SNR/SIR.



Element factor: measured vs omnidirectional





TMLA prototype

HARMONIC BEAMFORMING MEASUREMENTS



Phase imbalance

