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Principle of Smart and Reconfigurable Antennas and Selected Applications

Yevhen Yashchyshyn

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Outline

- Introduction
- Examples of Smart Antenna – Auditory and Electronic System
- What is a Smart Antenna? Why is Smart Antenna Important?
- Amplitude and Phase Weighting or Taper
- Beamforming
- Switched vs. Adaptive Beamforming
- Adaptive Array and Adaptive Beamforming
- Spatial Division Multiple Access (SDMA)
- Optimal beamforming Techniques (MMSE, LMS)
- Direction-of-Arrival Algorithms (Bartelett, Capon, MUSIC, ESPRIT)
- Reconfigurable antennas concepts
- SMILE - Spatial Multiplexing of Local Elements
- An Amplitude-Phase Weighting for Analog Microwave Beamforming
- Conclusion, References

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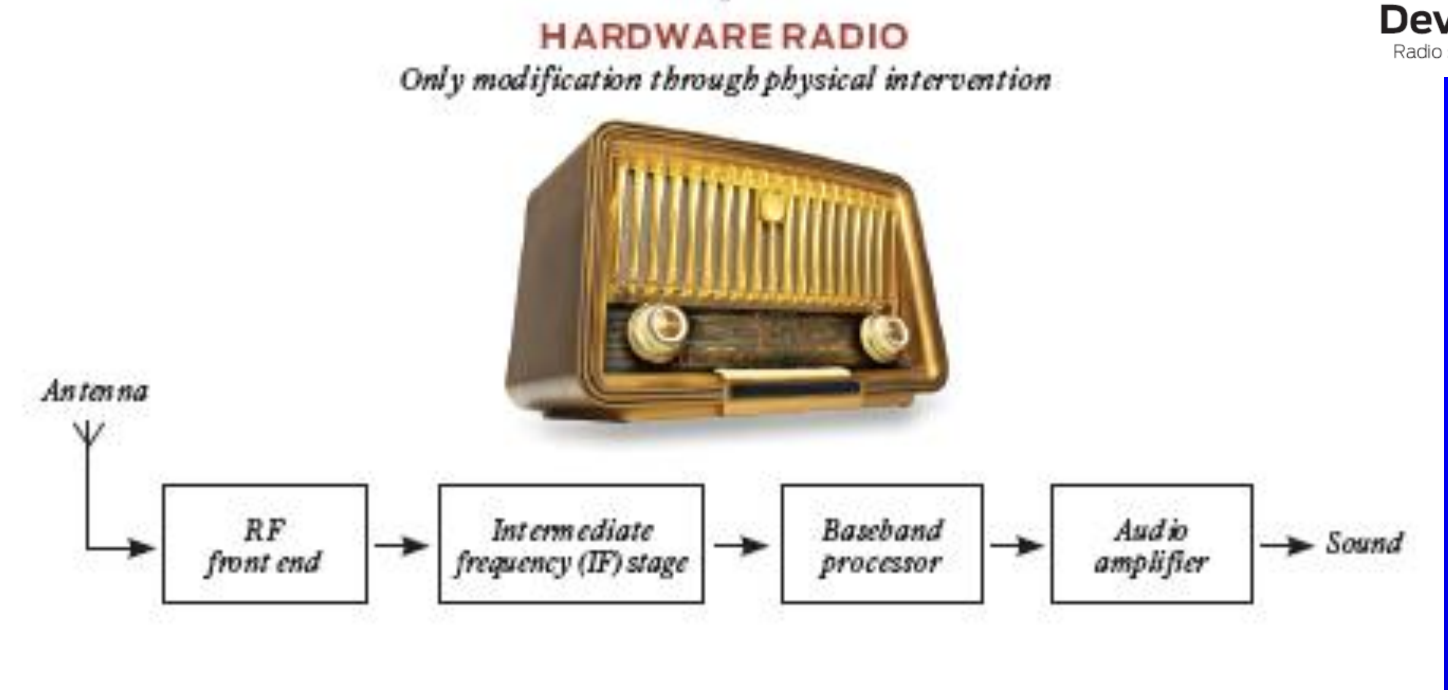
INTRODUCTION

Evolutionary Developments
Radio steps into the digital age



Time was when most radio sets had no software at all, and those that had any didn't do much with it. But Joseph Mitola III, an engineer working for a company called E-Systems (now part of Raytheon), envisioned something very different—a mostly digital radio that could be RECONFIGURED in fundamental ways just by changing the code running on it. In a remarkably prescient article he wrote in 1992 for the IEEE National Telesystems Conference, he dubbed it **software-defined radio** (SDR).

(IEEE Spectrum, vol.46, nr 4, 04.09) P. Koch, R. Prasad, The Universal Handset, Spectrum IEEE, April 2009, pp. 36-41

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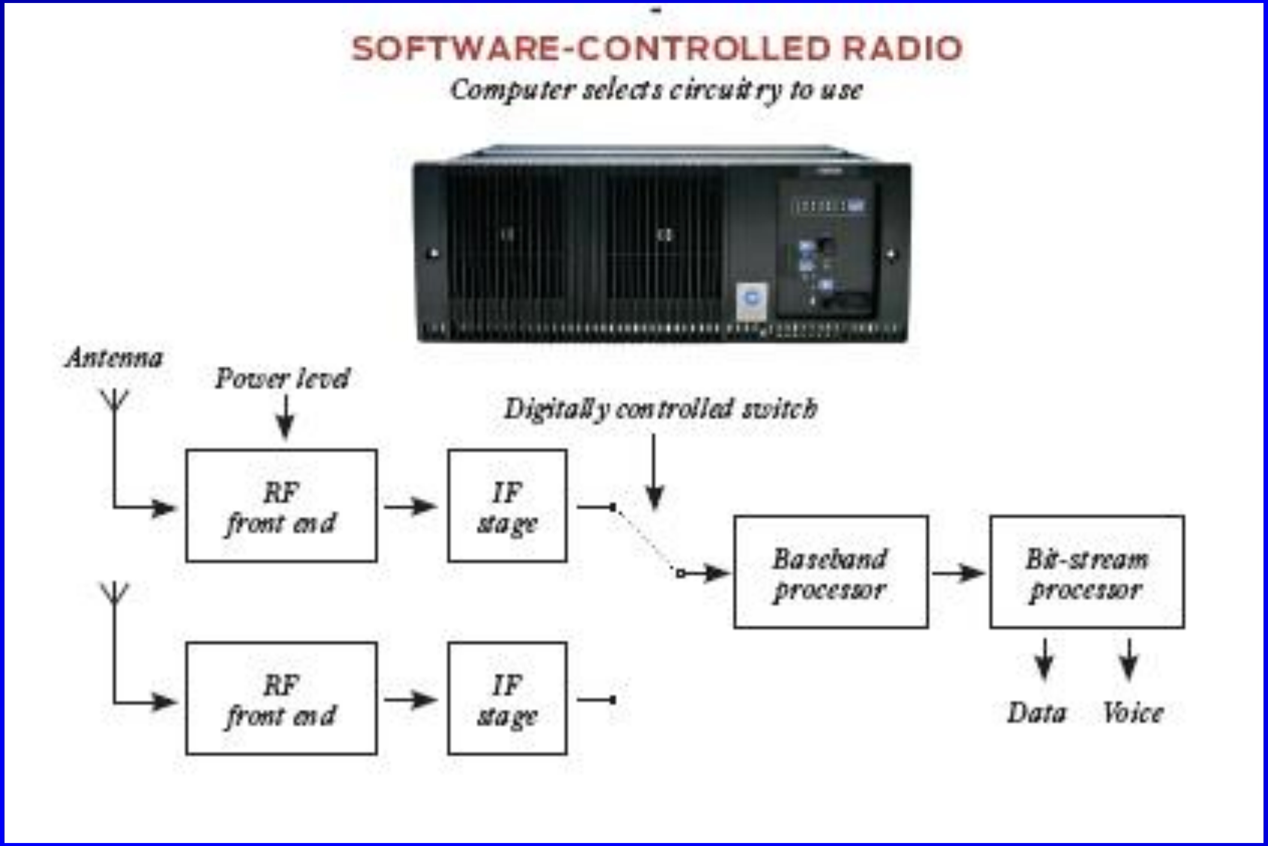
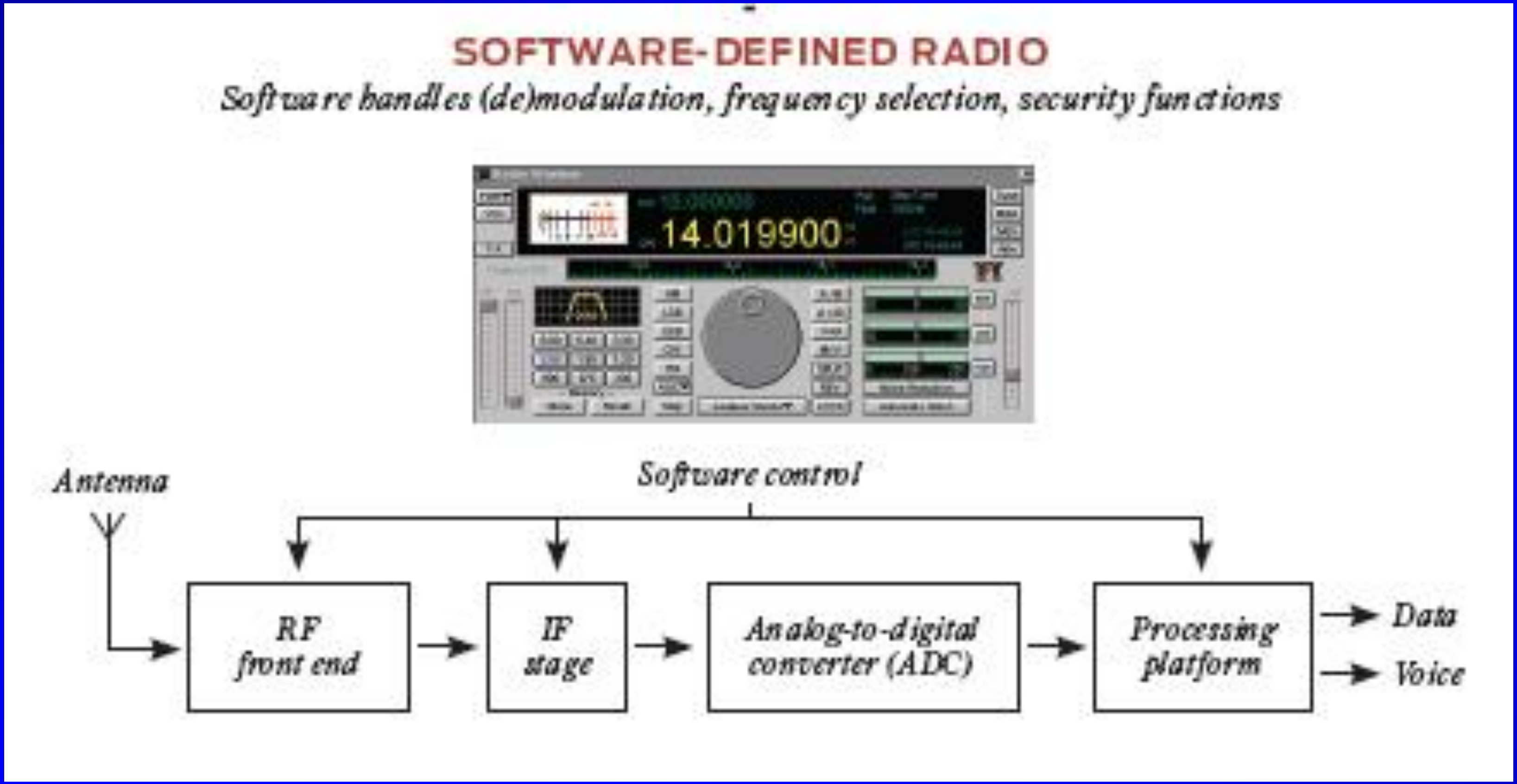


In some of today’s radios, software—often with the aid of digital hardware accelerators—does far more: It determines everything that happens to the signal after it’s converted from RF to lower frequencies and before it’s put in a form that’s suitable for your ears. In these radios, only the RF front end and the amplifier that powers the speaker still use analog components.



…The mid-1990s saw the radio systems in which software controlled most of the signal processing digitally, ENABLING ONE SET OF ELECTRONICS TO WORK ON MANY DIFFERENT FREQUENCIES AND COMMUNICATIONS PROTOCOLS. The first example was the U.S. military's Speakeasy radio, which allowed units from different branches of the armed forces to communicate effectively for the first time…

…. Perhaps the highest hurdle will be engineering the antenna, the size of which normally depends on the frequency of operation. Indeed, it’s very difficult to make a radio with an antenna that is not a significant fraction of a wavelength in size. This dictate of physics introduces a fundamental problem, because you’d ideally like a single compact antenna to cover everything from FM reception, at roughly 100 megahertz, to satellite-and personal-network communications, which operate in the few-gigahertz range…

….A radio intelligent enough to reconfigure itself—perhaps by detecting free spectrum and switching its frequency of operation to claim it—would make wireless services cheaper and more reliable for their users, most of whom will not even be aware that such marvelous things are going on under the hood.

Ah, to have a radio that not only switches function on demand but also configures itself into the most effective form possible without its user even knowing it. Now *that will be a truly universal handset.*

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Antenna’s role will radically change in future

- In future smart radios, the antenna will have a crucial importance in signal processing, picking up the wanted RF signal and preventing the unwanted signals from coming in by filtering them in the space, time and frequency domains.
- The antenna will also adapt itself to the changing transmission requirements and signal environments.
- The antenna’s physical structure will less than today limit it’s performance.
- The future antenna will be a reconfigurable aperture antenna that controls different parameters such as operation frequency, bandwidth, impedance match, and beam direction or width.
- However, major technology leaps in eg. material technologies or nonlinear innovation in design methods would be needed to fulfill all the expectations

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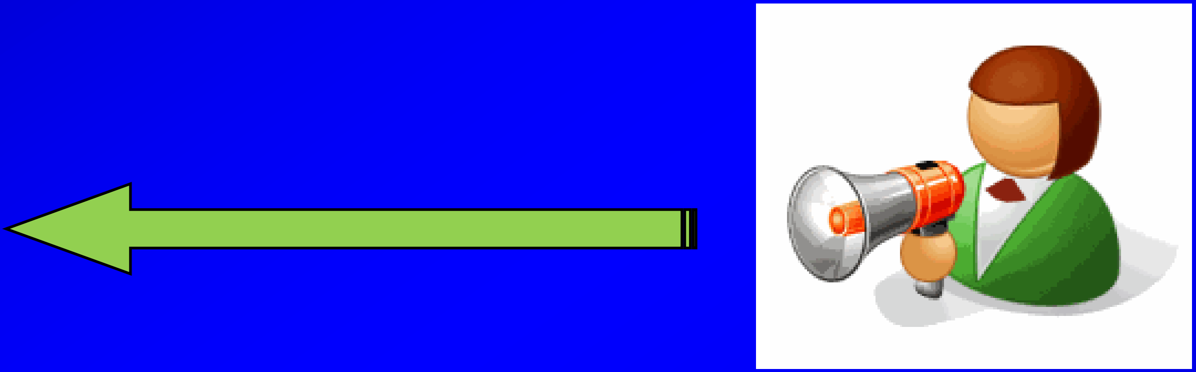
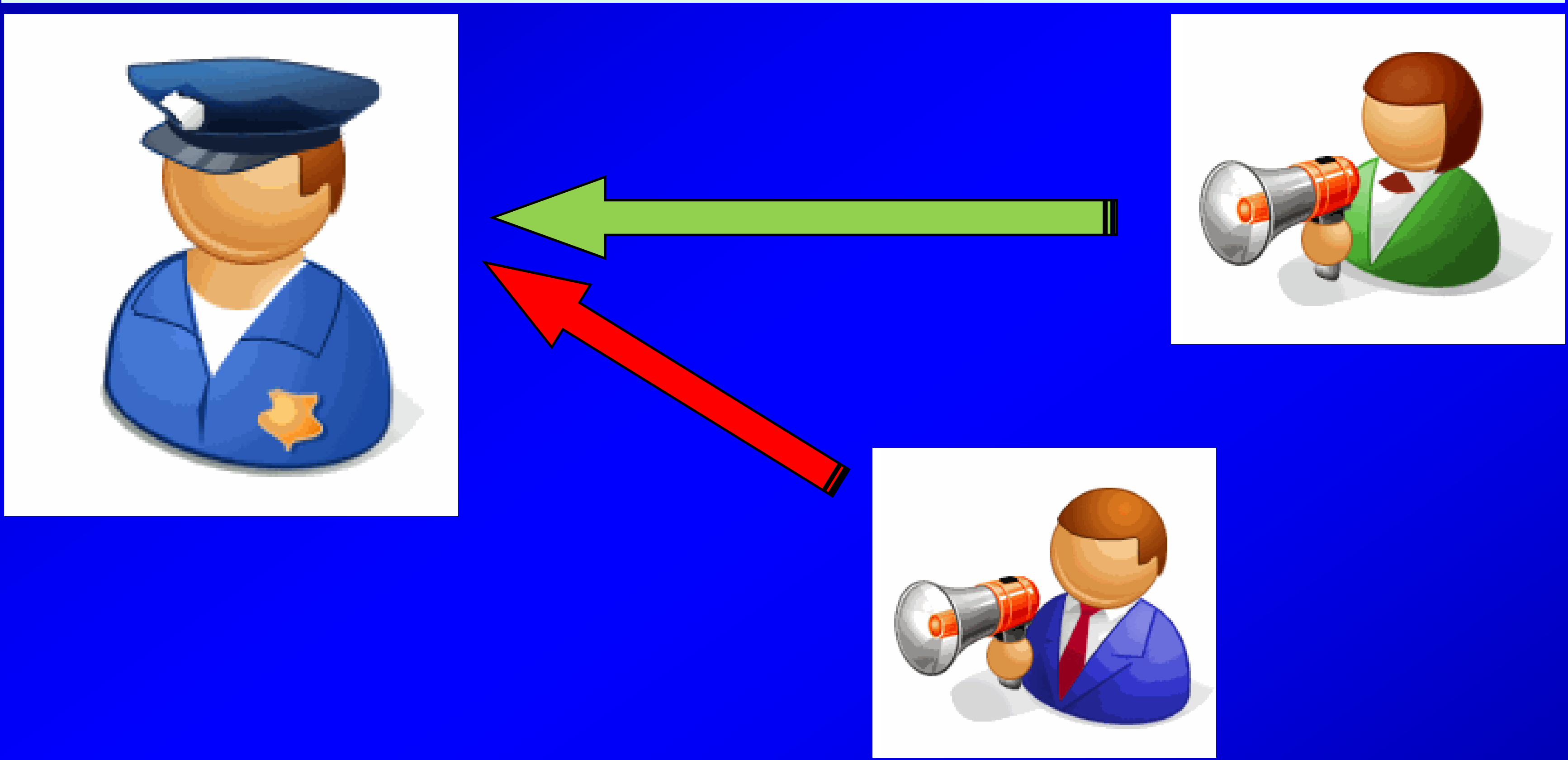
Smart Antenna – Auditory System



The listener can determine the location of a speaker without seeing him because of the following:

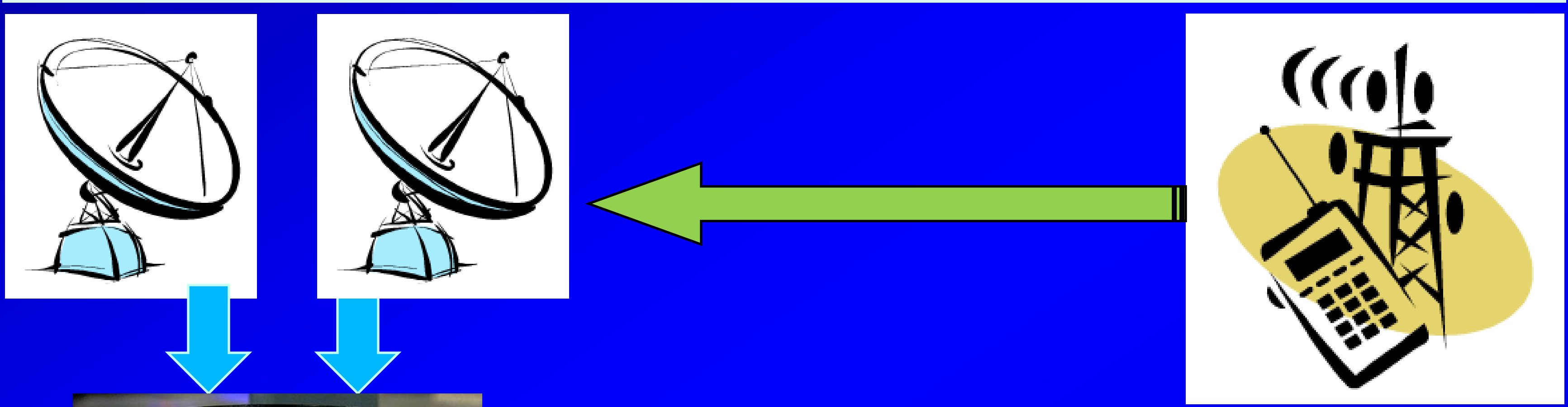
- **He hears the speaker’s voice through his two ears -** ***ACOUSTIC SENSORS***
- **The speaker’s voice arrives at each ear at different time -** ***TIME DELAY***
- **His brain, a specialized** ***SIGNAL PROCESSOR*****, computes the location of the speaker from the time delays**
- **His brain also adds** ***THE STRENGTH*** **of the signal from each ear together, so as the perceived sound in the computed direction is louder than everything else**

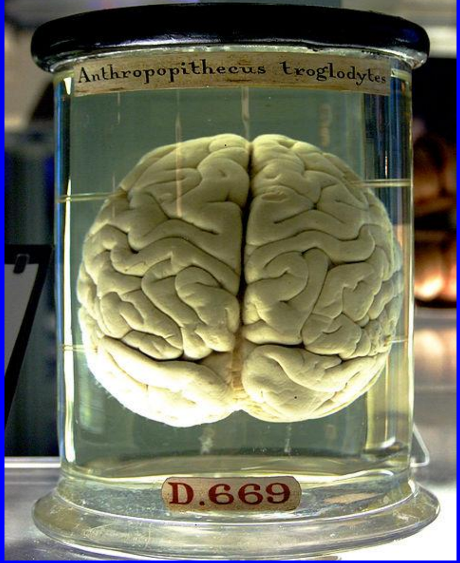
Smart Antenna – Auditory System



If additional speakers join in the conversation the listener's brain can tune out **unwanted interferers** and concentrate on one conversation at a time

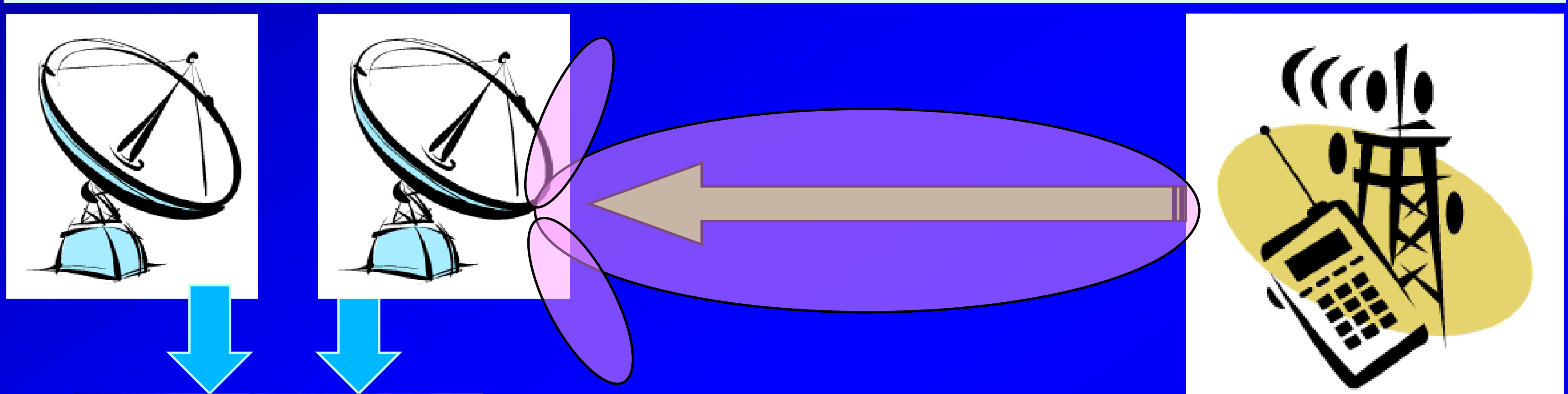
Smart Antenna – Electronic System

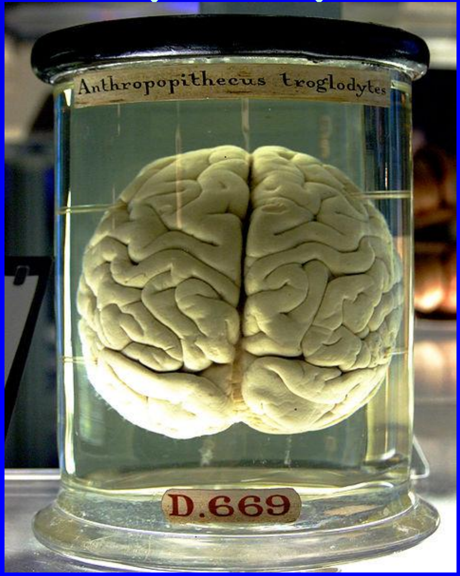




- It receives the user’s signal through its sensors – ***ANTENNA ELEMENTS***
- The signal arrives at each antenna at a different time - ***TIME DELAY***

Smart Antenna – Electronic System





Its DSP (*DIGITAL SIGNAL PROCESSOR*), computes the Direction-Of-Arrival (DOA) of the user from the time delay and also adds *THE STRENGTH* of the signal from each antenna element together and forms a beam toward the direction as computed by DOA

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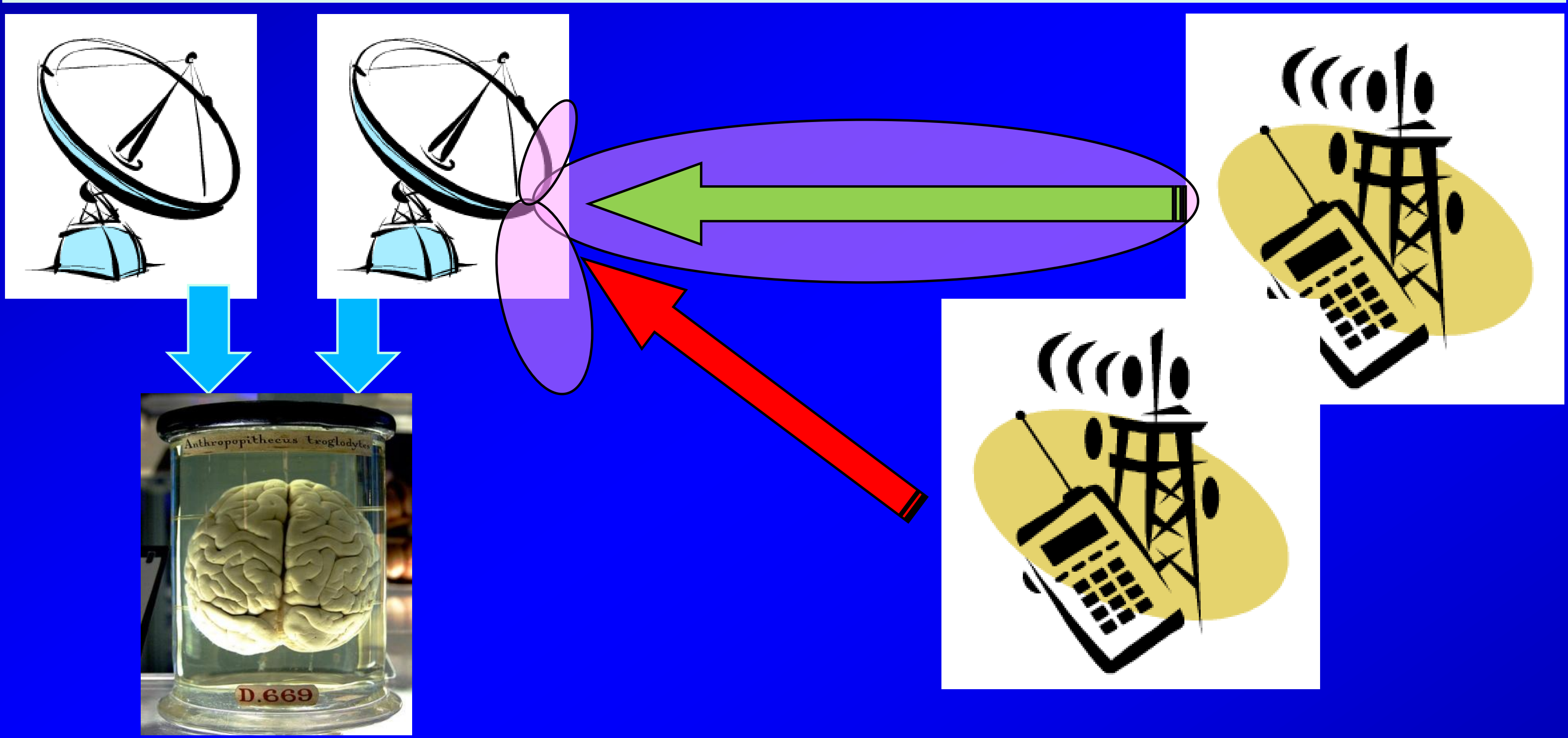
Smart Antenna – Electronic System



If additional users join in – the smart antenna system can tune out **unwanted interferers** **by** **placing nulls toward the Signal-Not-Of-Interest (SNOI),** and concentrate on the desired user by placing the main beam toward the **Signal-Of-Interest (SOI)**

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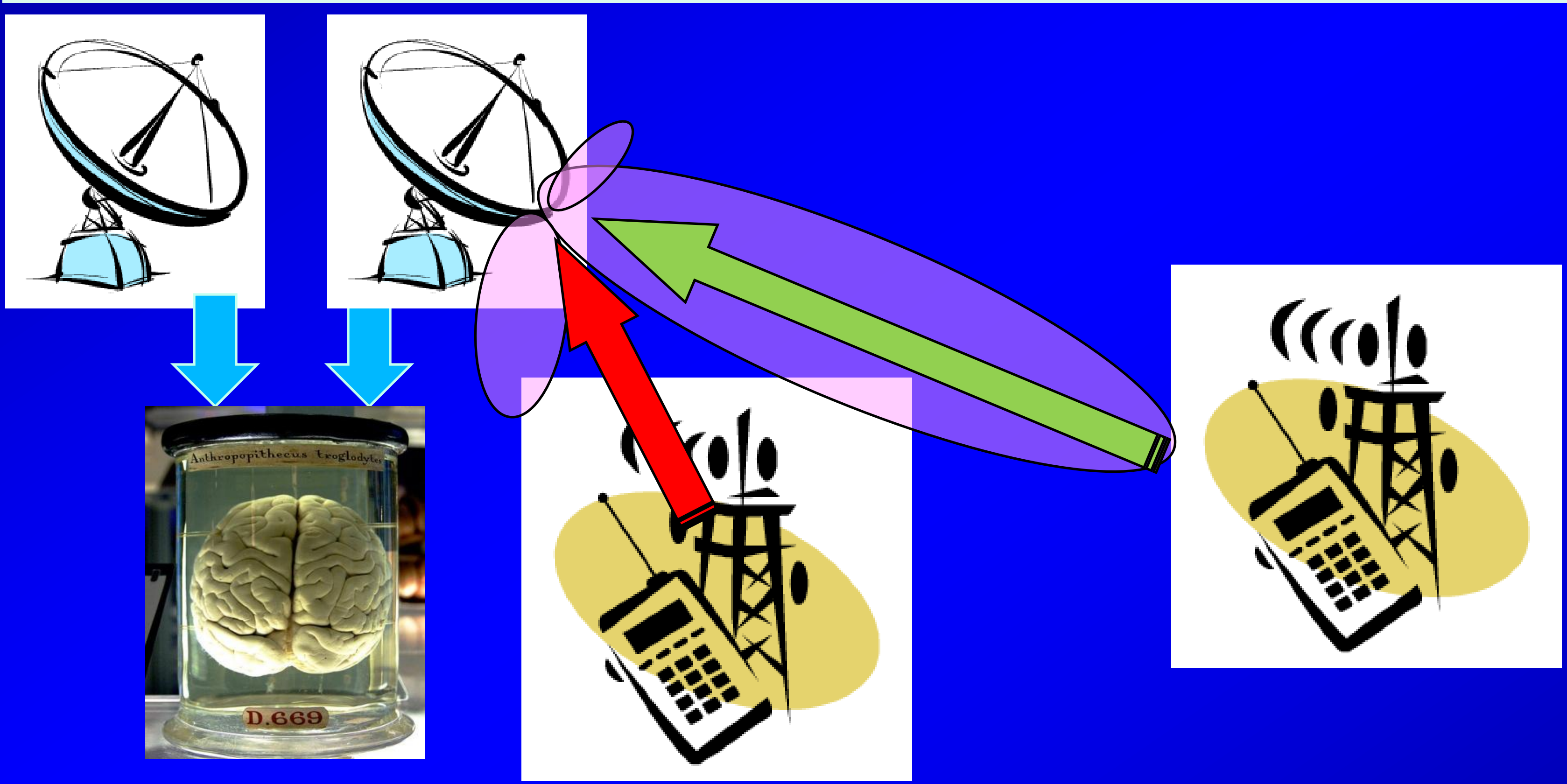
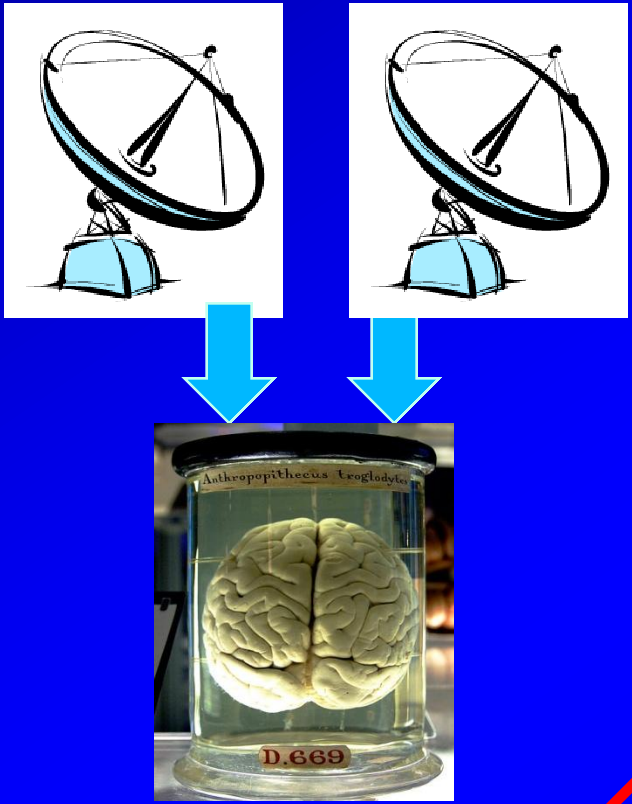
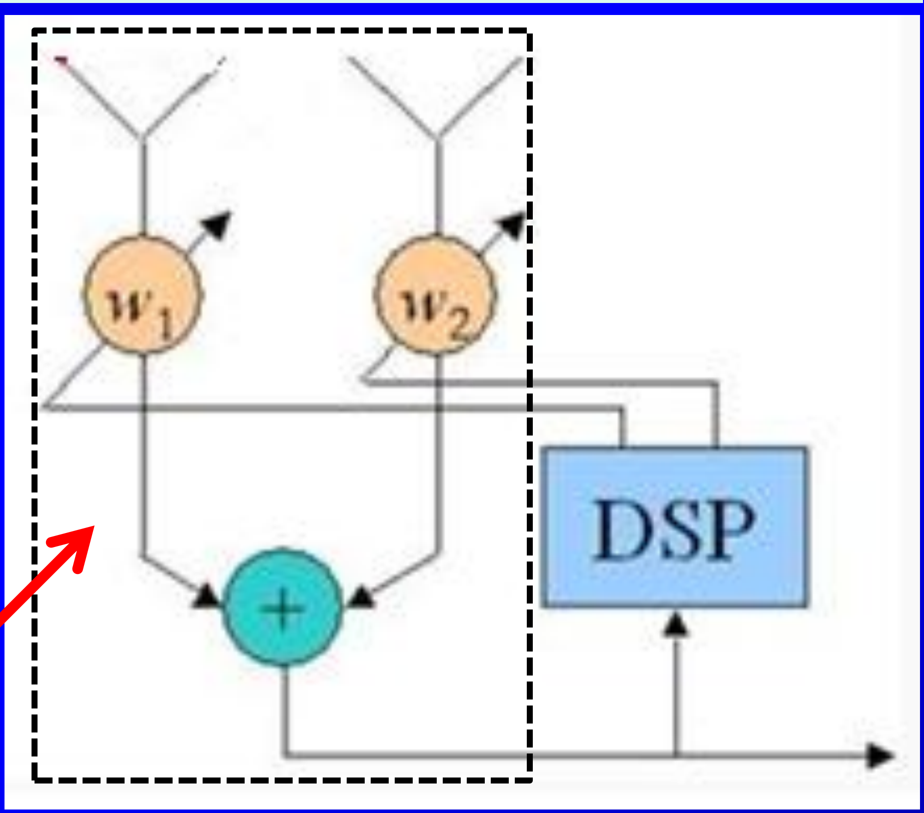
Smart Antenna – Electronic System



When users are moving the smart antenna system can dynamically change radiation pattern in reason to tune out **unwanted interferers by placing nulls toward the SNOI,** and concentrate on the desired user by placing the main beam toward the **SOI**

What is a Smart Antennas?





Smart antenna systems combine:

Antenna arrays + **DSP algorithms** (to make the antenna system „smart”)

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Why is Smart Antenna Important?

Smart Antennas integrate radio intelligence (DSP) with antenna array technology to:

Enhance communication system performance, including:

1.Capacity

2. Range

Improve link quality, for transmission and recepttion, by:

1. Multipath management

2. Mitigation of fading

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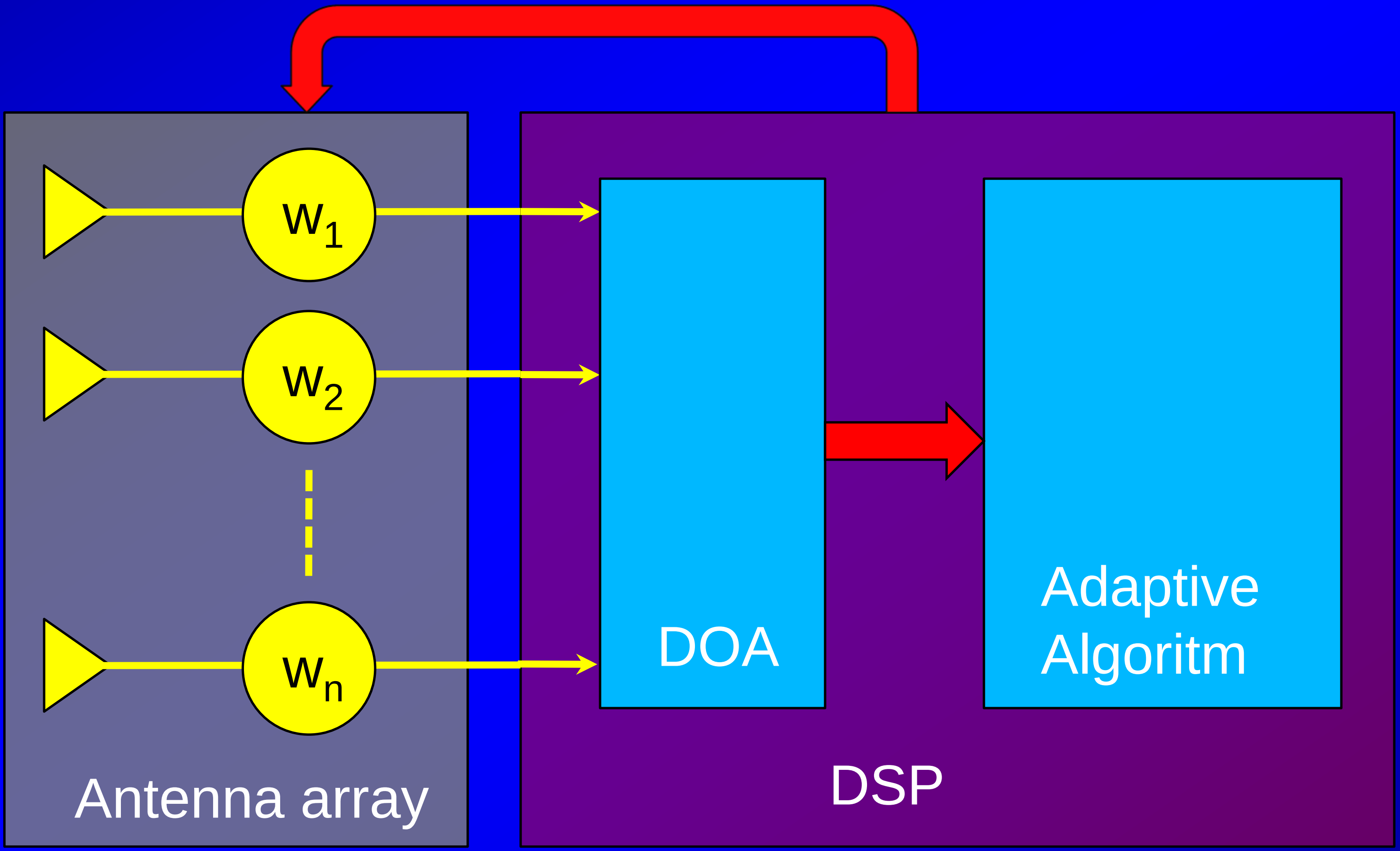
Why is Smart Antenna Important?

Enhancing communication system performance and Improving link quality are accomplished by:

1. ***Beam steering*** – placing beam maximuma toward Signals Of Interest (SOI)
2. ***Null steering*** – placing beam minima (ideally nulls) toward interfering signals (Signal Not Of Interest – SNOI)
3. ***Spatially separate signals*** – Allowing different users to share the same spectral resources (SDMA)

Smart Antenna



DOA – direction of arrival; DSP – digital signal processor

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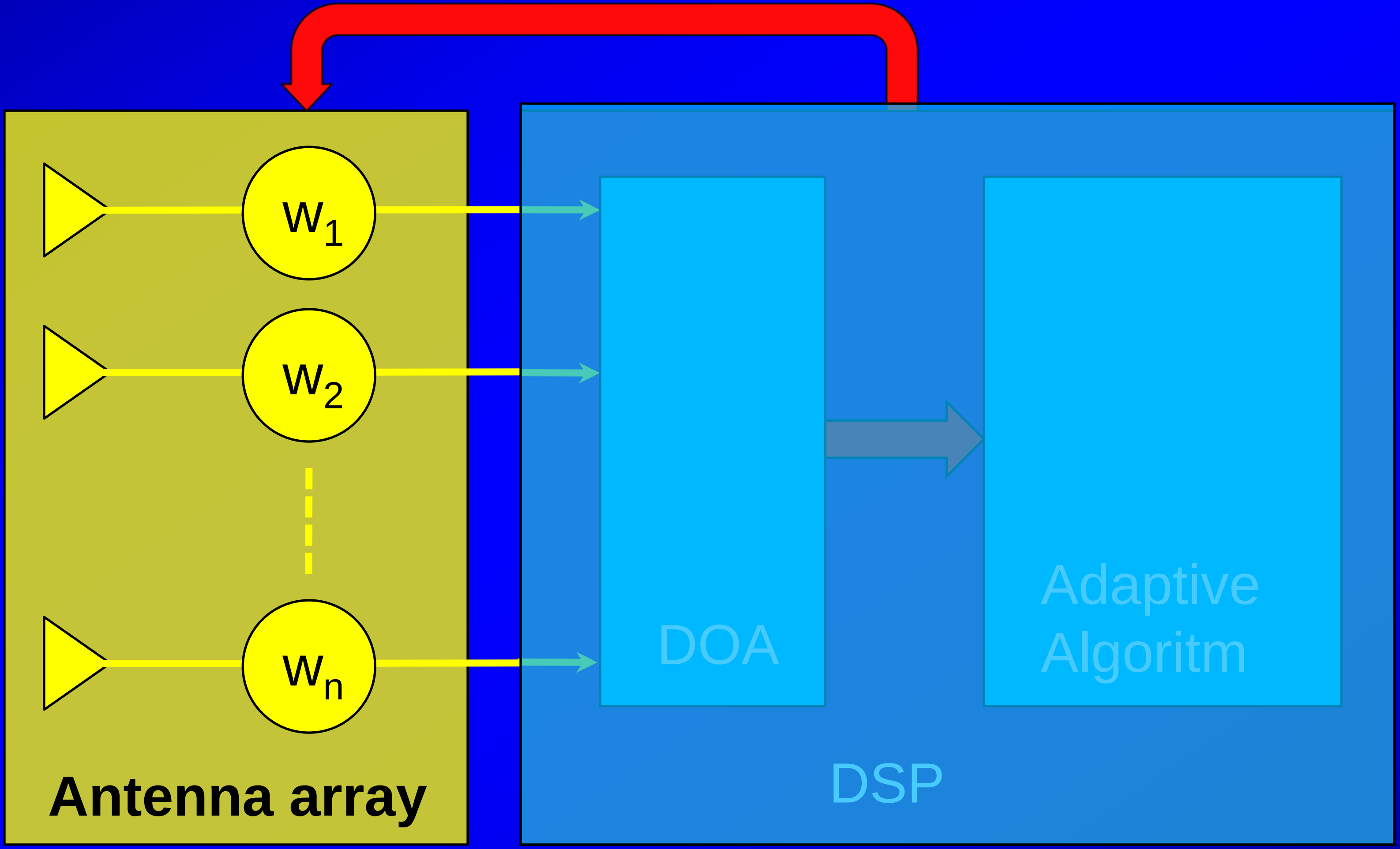
Antenna Array



DOA – direction of arrival; DSP – digital signal processor

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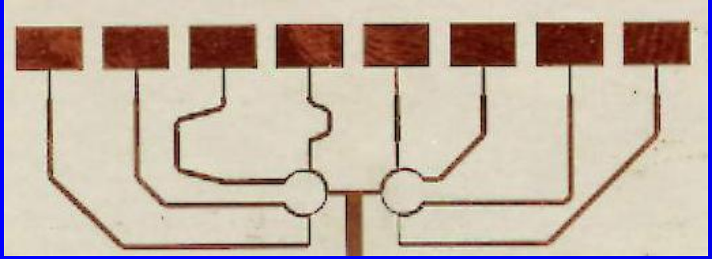
Antenna Types

Base station antenna for mobile phones

Microwave relay

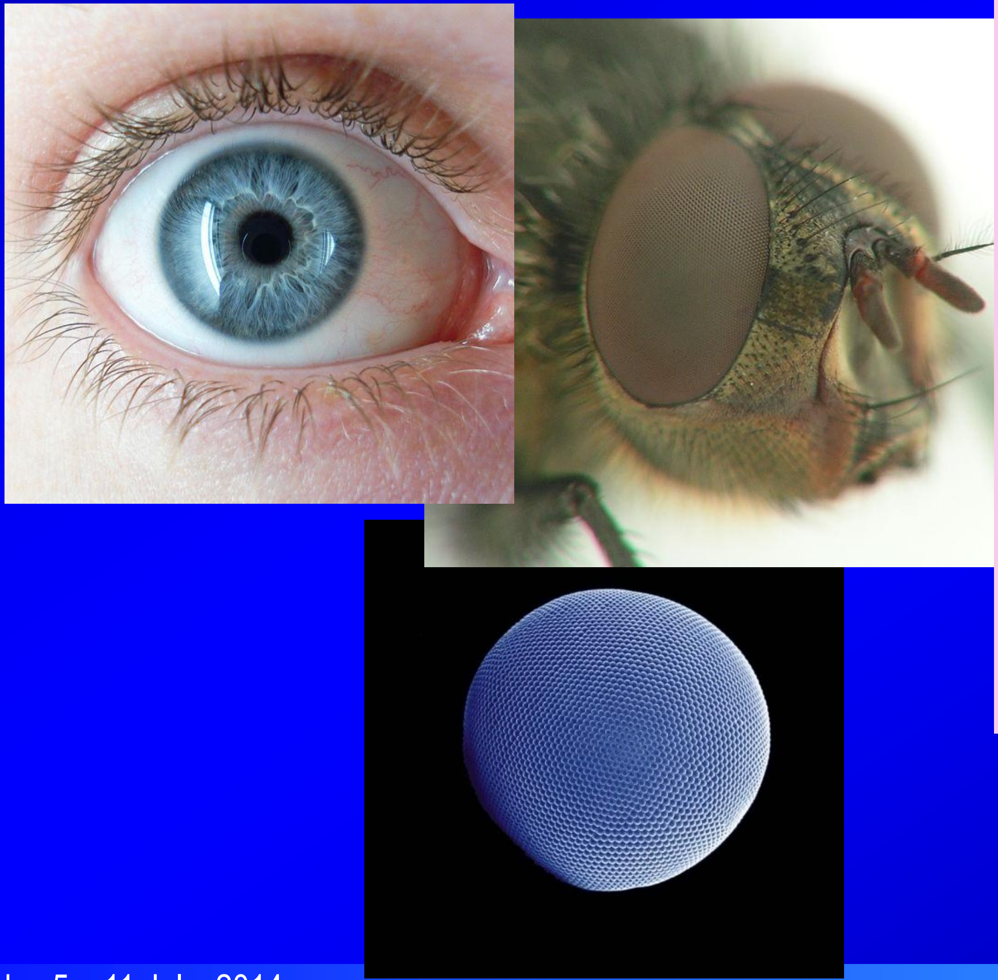
Wall-mount base-station antenna

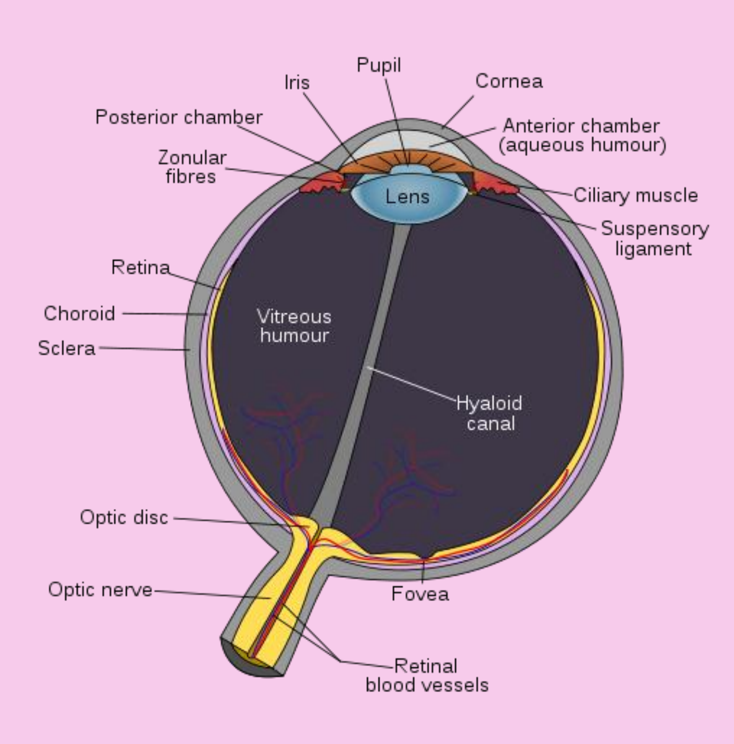


Shaped-beam antenna

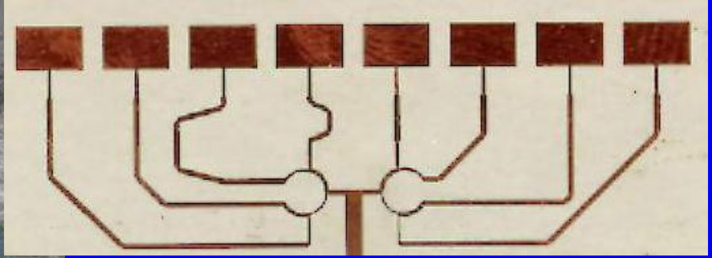
Antenna Types

Example from nature – antenna of optical band – eye





Array Antenna



Antenna formed by multielements is refered as an **ARRAY**

In most cases, the elements of an array are identical (this is not necessary, but it is often convenient, simpler and more practical)

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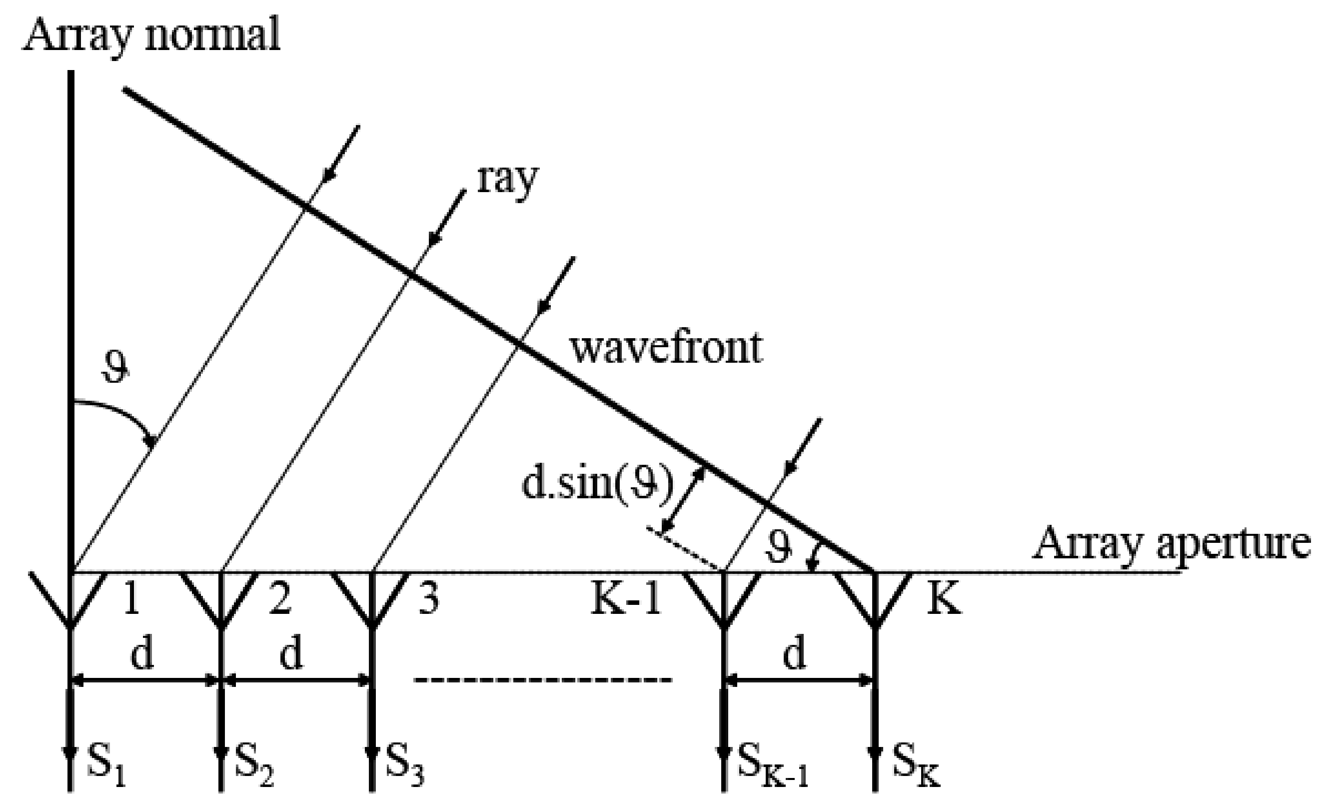
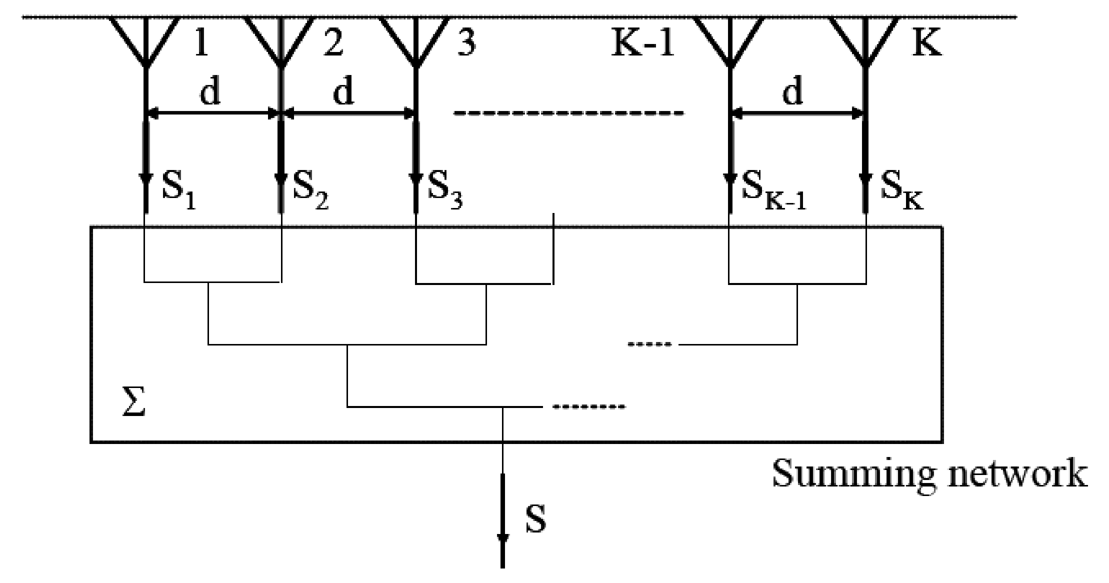
Linear Array Antenna

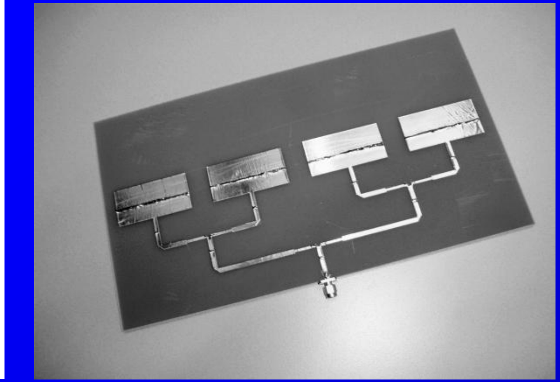


A linear array of K radiators, equidistantly positioned along a straight line, where a plane wave is incident under an angle θ with respect to the array normal

Linear Array Antenna



A linear array antenna with equal path length summing network



The complex signal received by the elements of the array antenna, $S_i(\theta)$, may be written as

$$S_i(\theta)=S_e(\theta)a_i e^{jk_0(K-i)d\sin\theta} \quad for\ i=1,2,...,K,$$

where $S_e(\theta)$ *represents the complex radiation pattern of the one (isolated*) radiator and a_i is the amplitude received by the i^{th} element.

For the moment we assume that all amplitudes received by the elements are equal and normalised to one, i.e.:

$$a_i=1 \quad for\ i=1,2,...,K,$$

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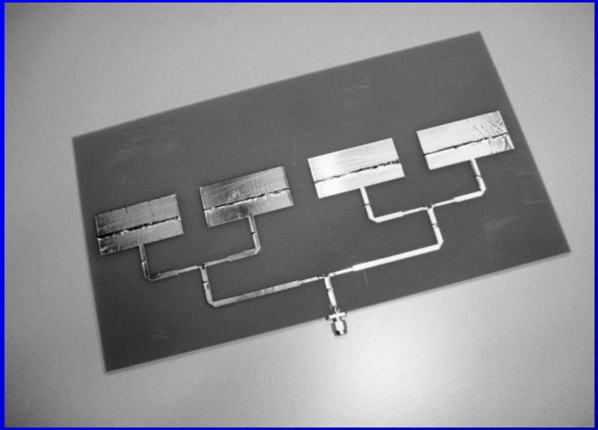
Linear Array Antenna

If we combine all received signals without introducing additional phase differences between the elements, we may simply add the received signals described by equation has shown above for all elements *i*. The total received signal, *S(θ), is then found to be*

$$S(\theta)=\sum_{i=1}^{K}S_i(\theta)=S_e(\theta)\sum_{i=1}^{K}e^{jk_0(K-i)d\sin\theta}$$

It sees that the received signal may be separated in a component due to a single radiator and in a component due to the array configuration only

$$S(\theta)=S_e(\theta)\cdot S_a(\theta)$$



Where $S_e(\theta)$ is known as the ***element factor*** and

$$S_a(\theta)=\sum_{i=1}^{K}e^{jk_0(K-i)d\sin\theta}$$

is known as the ***array factor***

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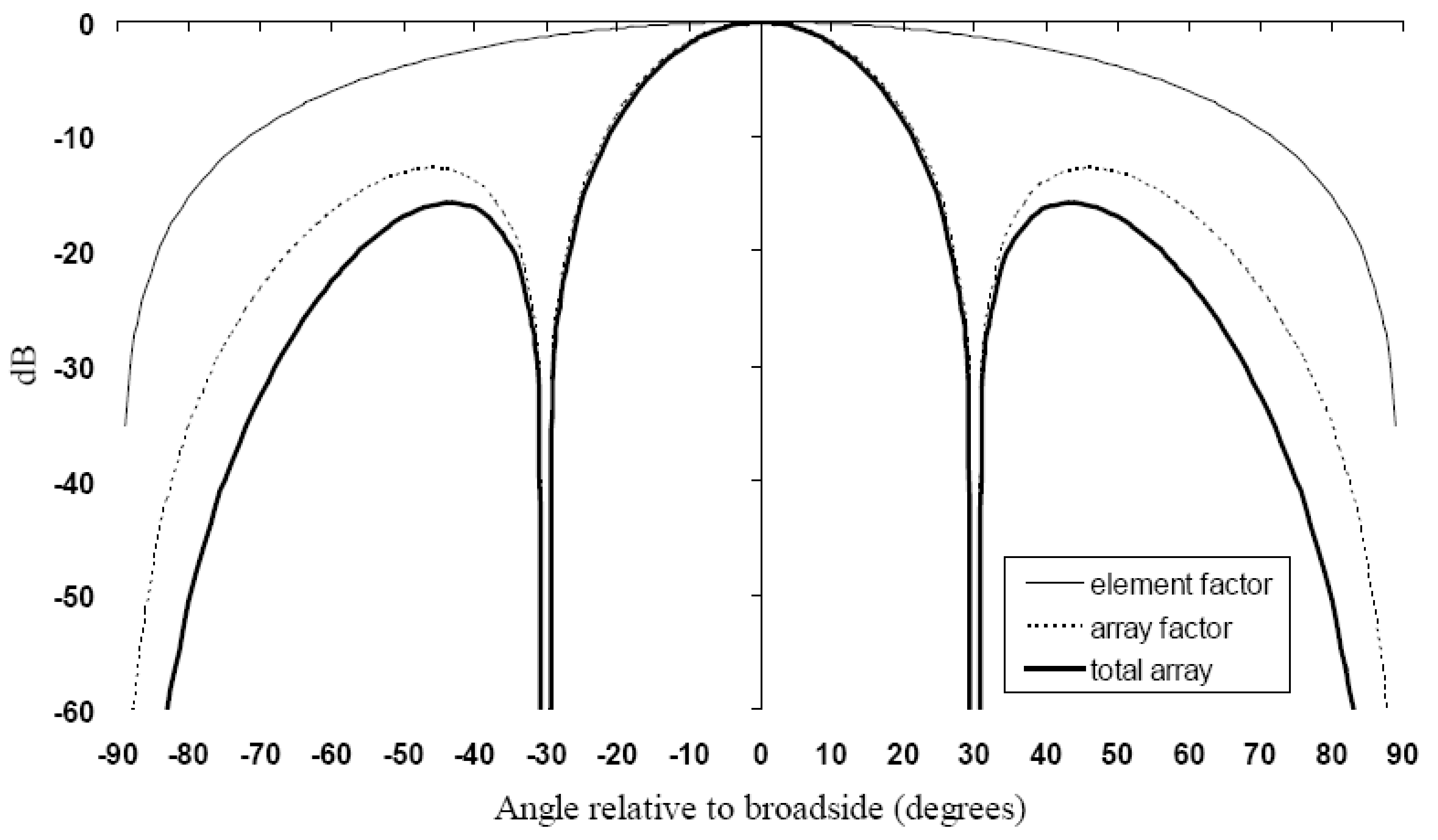
Example: Linear Array Antenna of eight elements for d=$\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$



Power radiation patterns of the element factor, the array factor and total array (d=$\lambda_0/4$)

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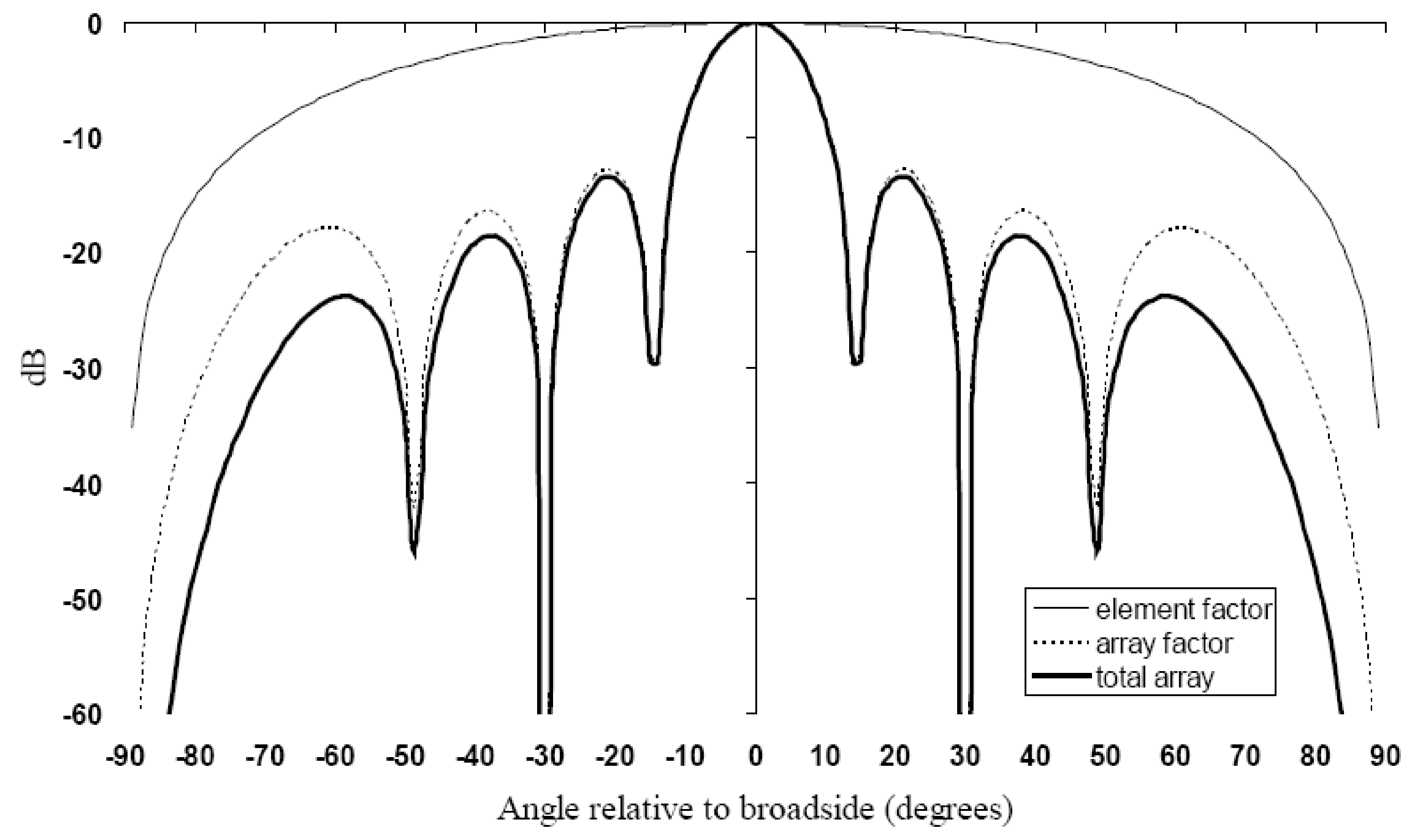
Example: Linear Array Antenna of eight elements for d=$\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$



Power radiation patterns of the element factor, the array factor and total array (d=$\lambda_0/2$)

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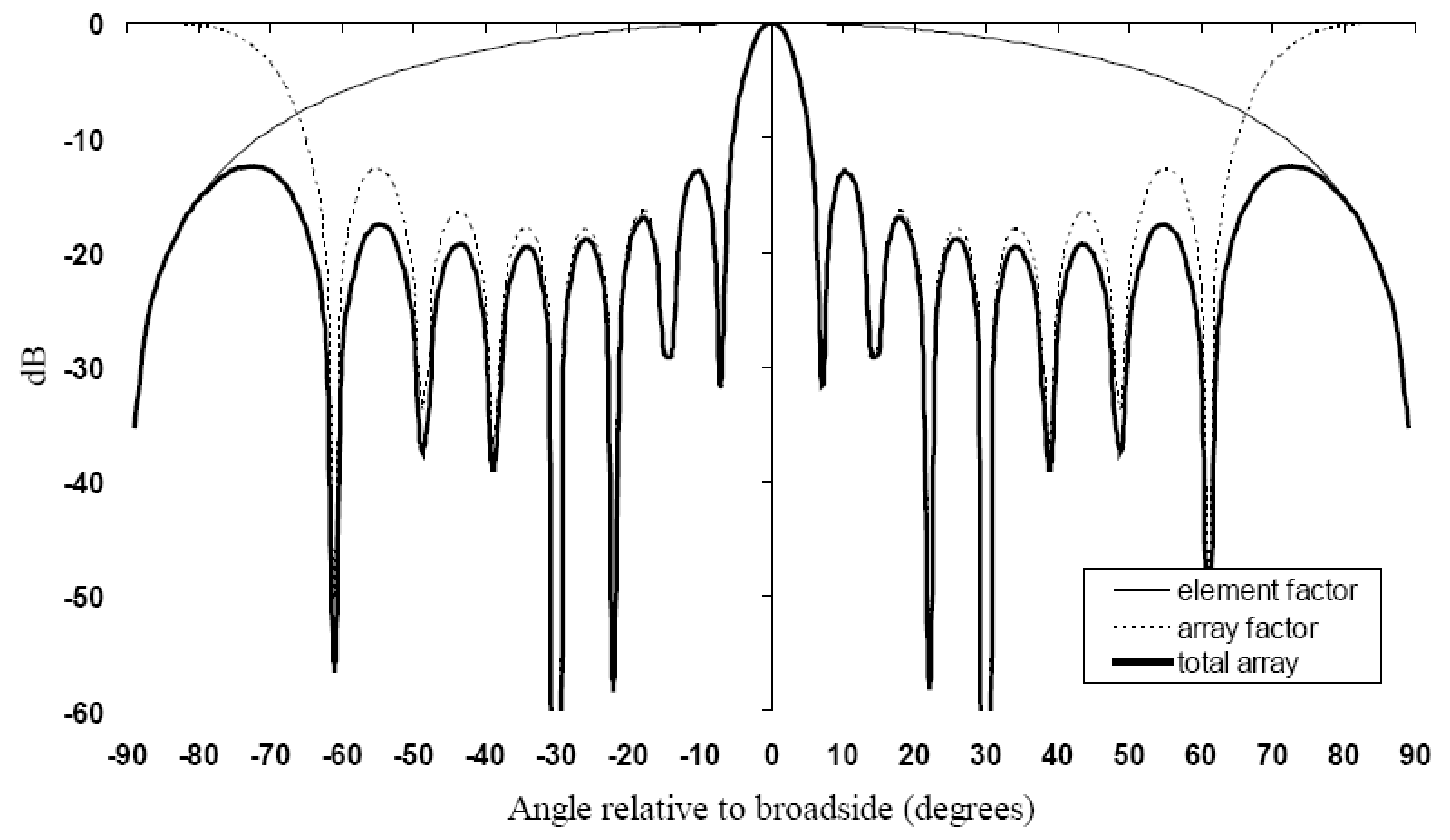
Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$



Power radiation patterns of the element factor, the array factor and total array ($d=\lambda_0$)

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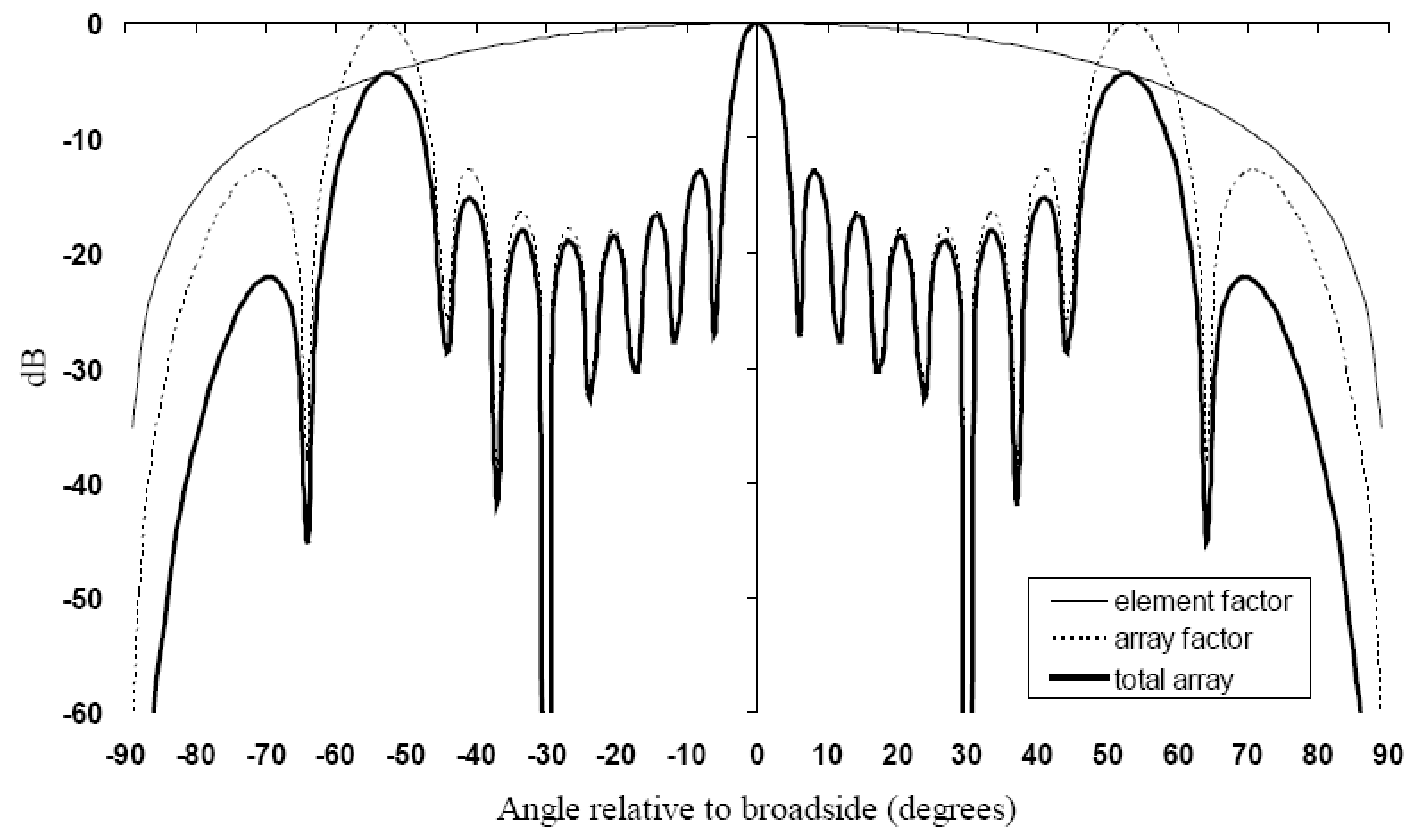
Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$



Power radiation patterns of the element factor, the array factor and total array ($d=5\lambda_0/4$)

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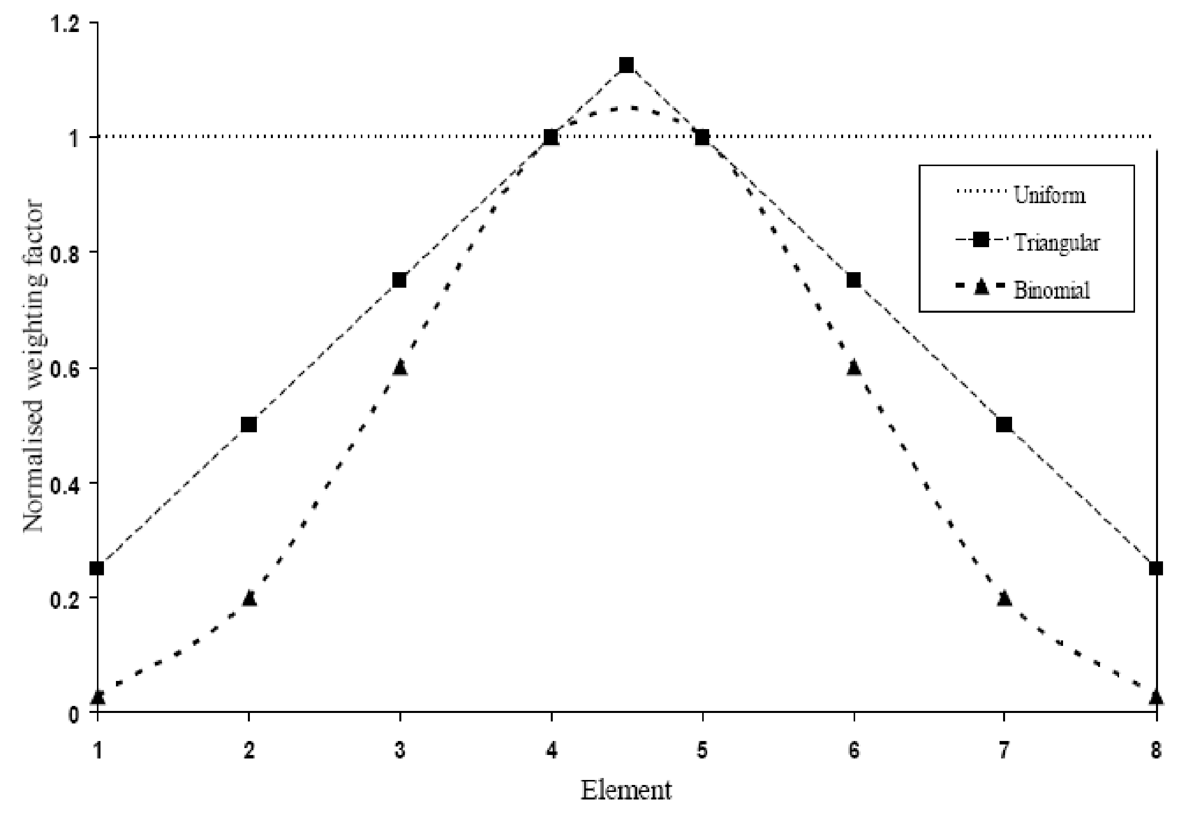
Amplitude Weighting (K=8; d=λ_0/2)



Amplitude weighting or taper for a linear 8-element brodside array with element distance d=λ/2

Uniform, triangle and **binominal** amlitude taper, normalised to unity at the central elements

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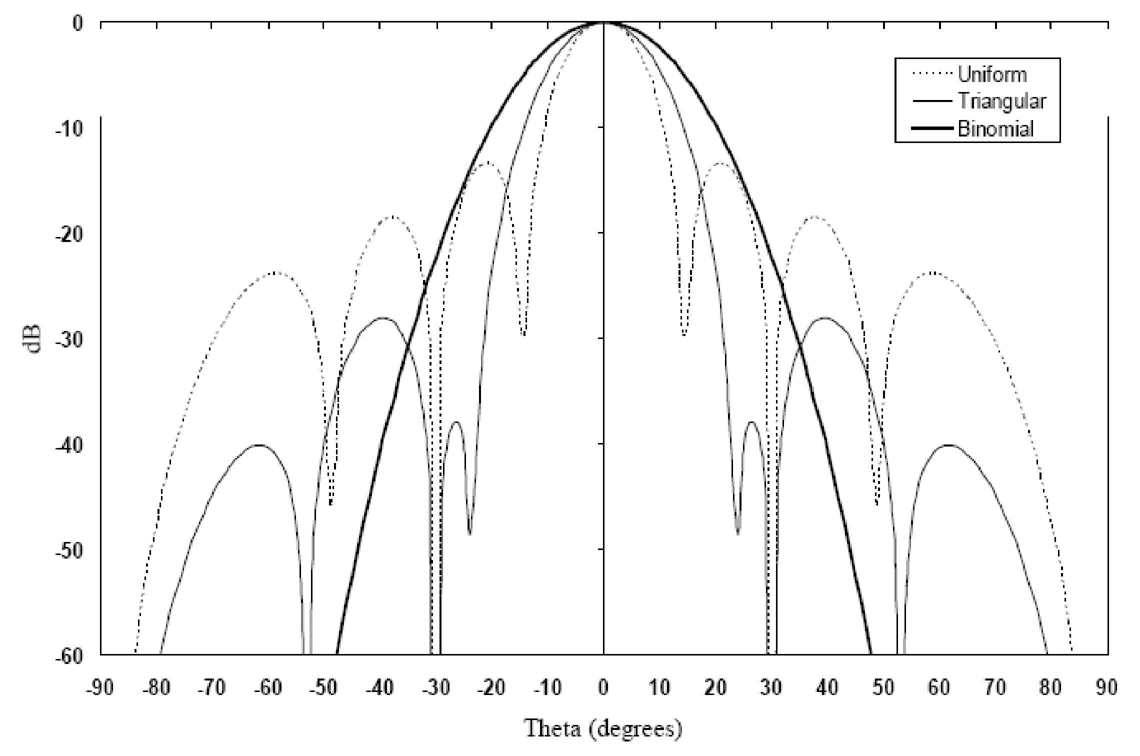
Power radiation patterns of the array (K=8; d=$\lambda_0/2$) for **uniform, triangle** and **binominal** amlitude taper



Triangle amplitude taper leads to a **lower side lobe level** compared to the one obtained for a **uniform amplitude taper**.

It appears to be even possible to **remove the side lobes all together**, by choosing the amplitude coefficients equal to the coefficients of a **binominal series.**

Broadening of the beam to be paid as price for the removal of the side lobes.

Why is an amplitude taper important for smart antenna?

Smart Antenna Systems – by means of an *internal feedback control*, they can generate a customized radiation pattern to each remote user. In general, they form a main lobe toward a desired user and rejects interference outside the main lobe.

„+”: We can shape radiation pattern by changing the amplitude taper:

- **lower side lobe level**
- **shift the nulls of radiation pattern**
- **broaden the main beam**

„-”: We can not change the main beam direction

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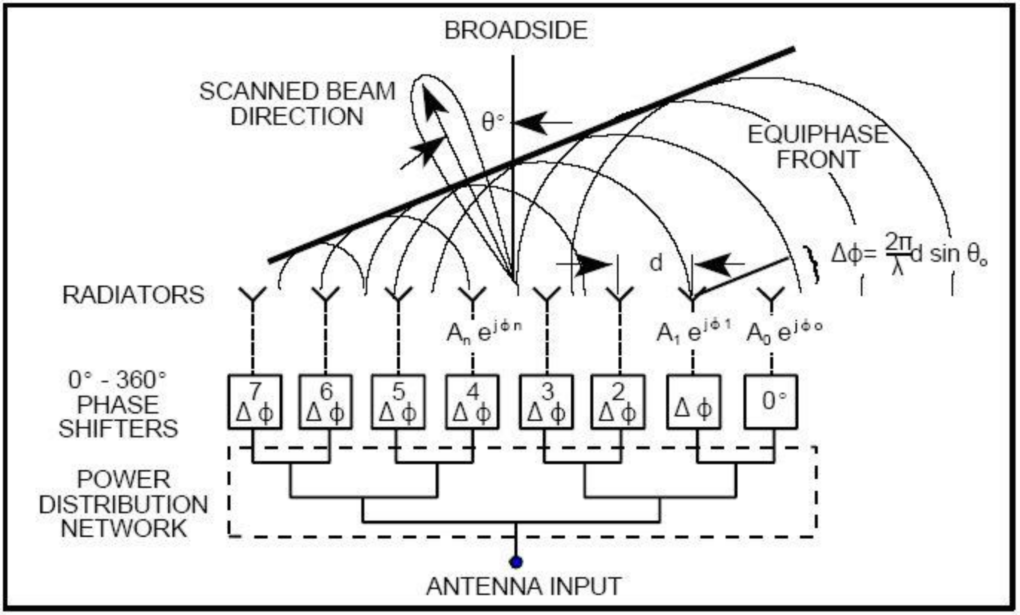
Linear Phased Array Antenna



a **phased array** is a group of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions

Patriot radar,
image from Wikipedia.com

Courtesy of Alaska District, this 90-foot (27m) diameter radar installation monitors the northern sky. Its construction was part of the Clear Radar Upgrade to make all Ballistic Missile Early Warning System radars phased-array rather than mechanical.

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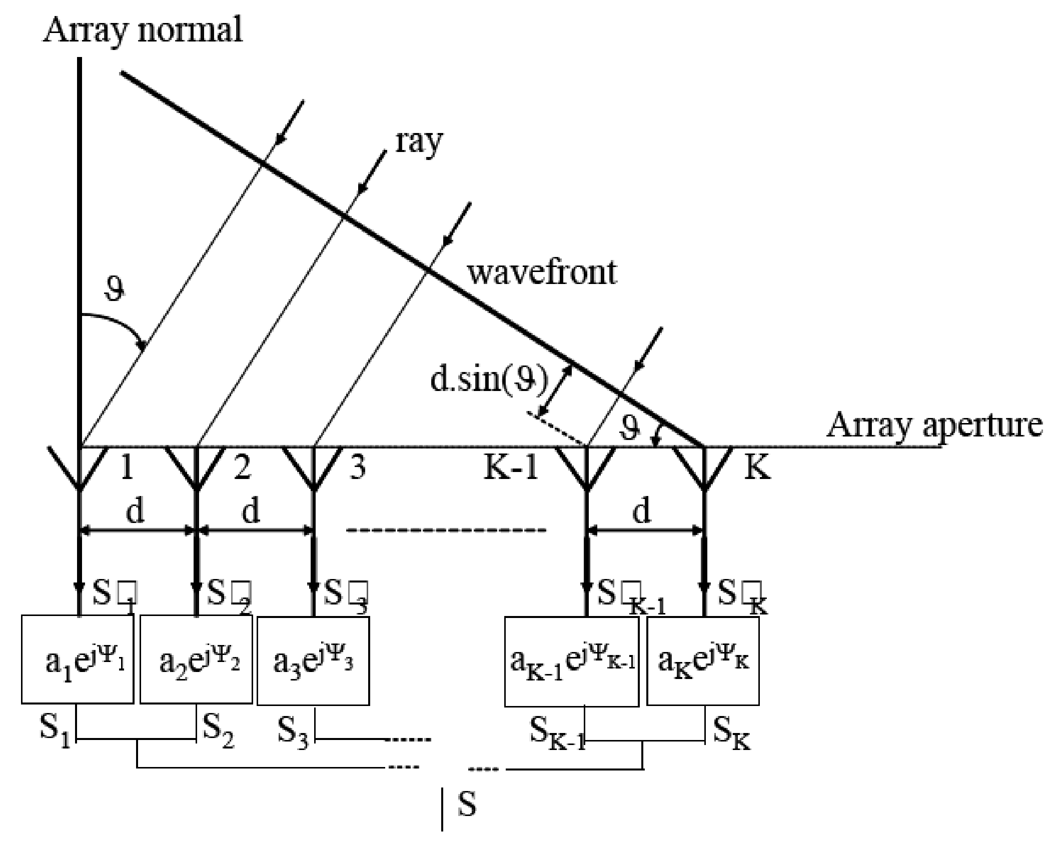
Linear Phased Array Antenna



A linear array of K radiators, equidistantly positioned along a straight line, where a plane wave is incident under an angle θ with respect to the array normal. The difference with the previous situations (broadside linear array antenna) is that now, in the (corporate) feed network, we add a microwave two-port between every antenna element and its branch of the feed network.

The two-port will allow us to change the ***amplitude*** of every received signal and – what is more important for the moment – it will allow us to change the ***phase*** of the received signal. The two-ports open up the opportunity to operate a ***phased array antenna***.

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Linear Phased Array Antenna

If we combine all received signals with introducing additional phase differences between the elements, we may simply add the received signals described by equation has shown above for all elements *i*. The total received signal, *S(θ),* is then found to be

$$S(\theta)=\sum_{i=1}^{K}S_i(\theta)=S_e(\theta)\sum_{i=1}^{K}a_i e^{j\left[k_0(K-i)d\sin\theta+\psi_i\right]}$$

In this equation we implicitly have assumed that mutual coupling effects between the array antenna elements are negligible, allowing for a common element radiation pattern that is taken out of the summation.

All the coefficients a_i form the amplitude taper. In order not to obscure the phased array antenna discussion, we assume a uniform, normalised amplitude distribution:

$$a_i=1 \quad for\ i=1,2,\ldots,K,$$

So, by choosing a desired beam-pointing direction θ_0 an subsequently phasing the linear array antenna elements according to $\psi_i=-k_0(K-i)d\sin\theta_0$, the array factor will have its maximum at the desired angle $\theta=\theta_0$

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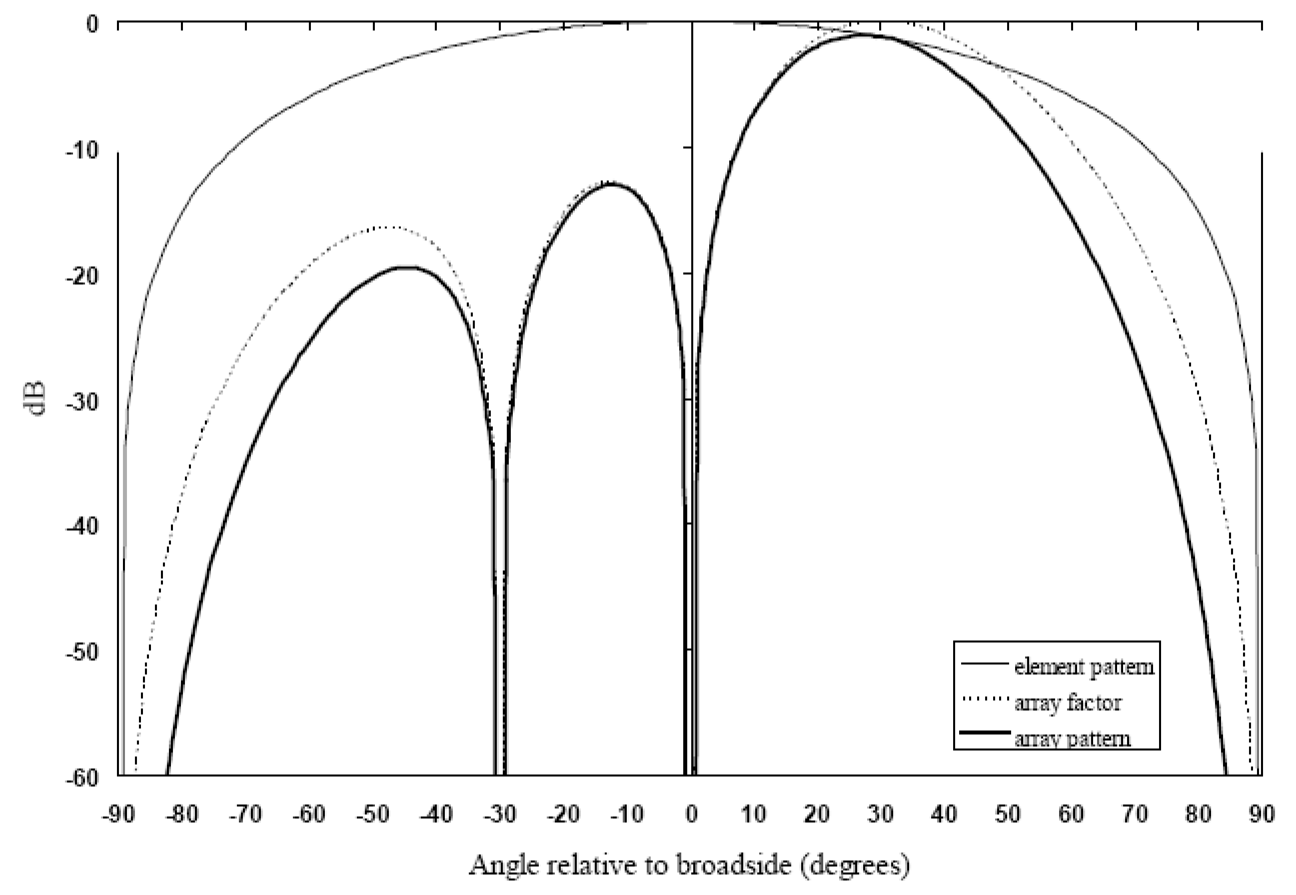
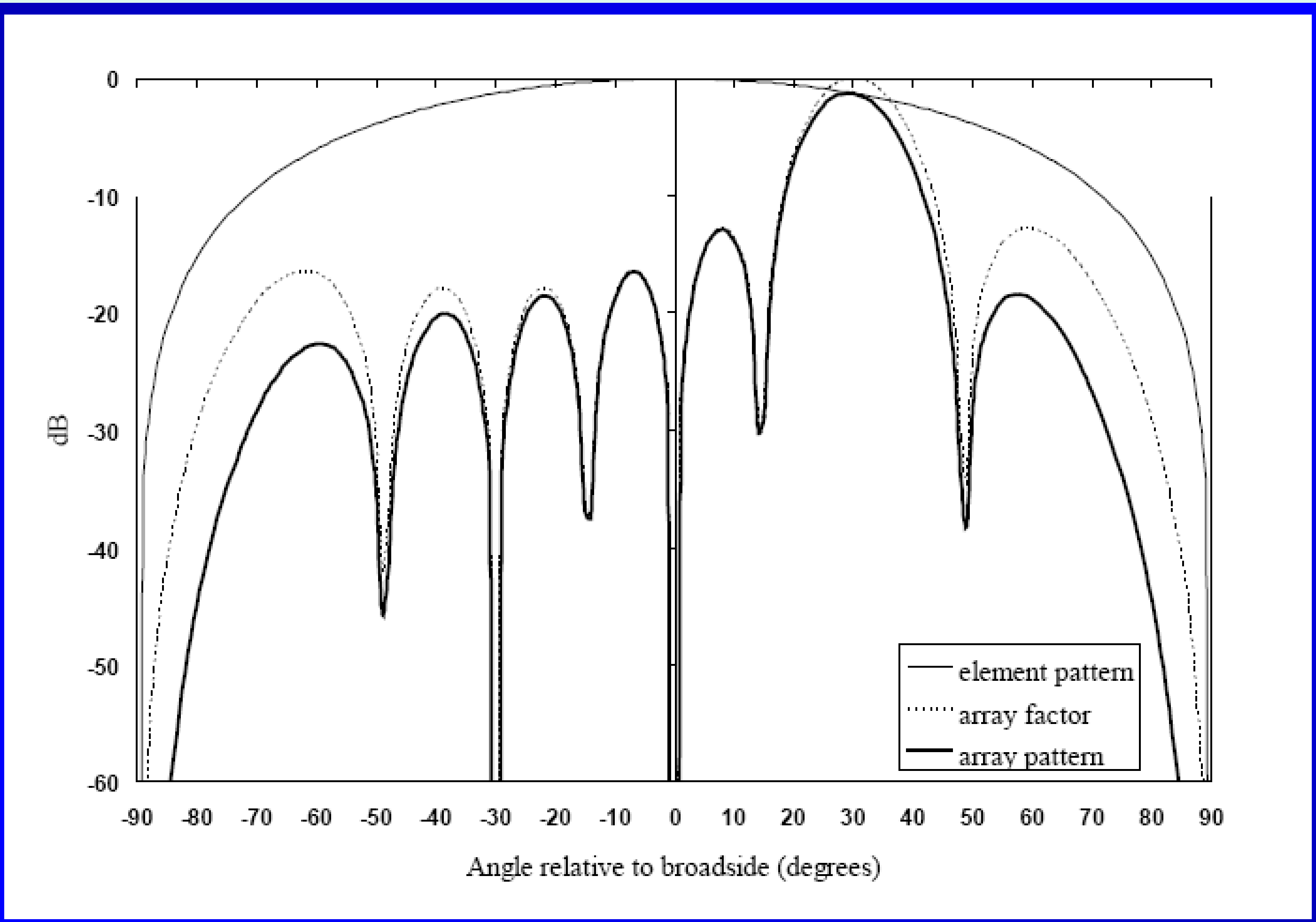
Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$; *beam pointing* $\theta_0=30^0$



Power radiation patterns of the element factor, the array factor and total array ($d=\lambda_0/4$) and *beam pointing* $\theta_0=30^0$

Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$; *beam pointing* $\theta_0=30^0$



Power radiation patterns of the element factor, the array factor and total array ($d=\lambda_0/2$) and *beam pointing* $\theta_0=30^0$

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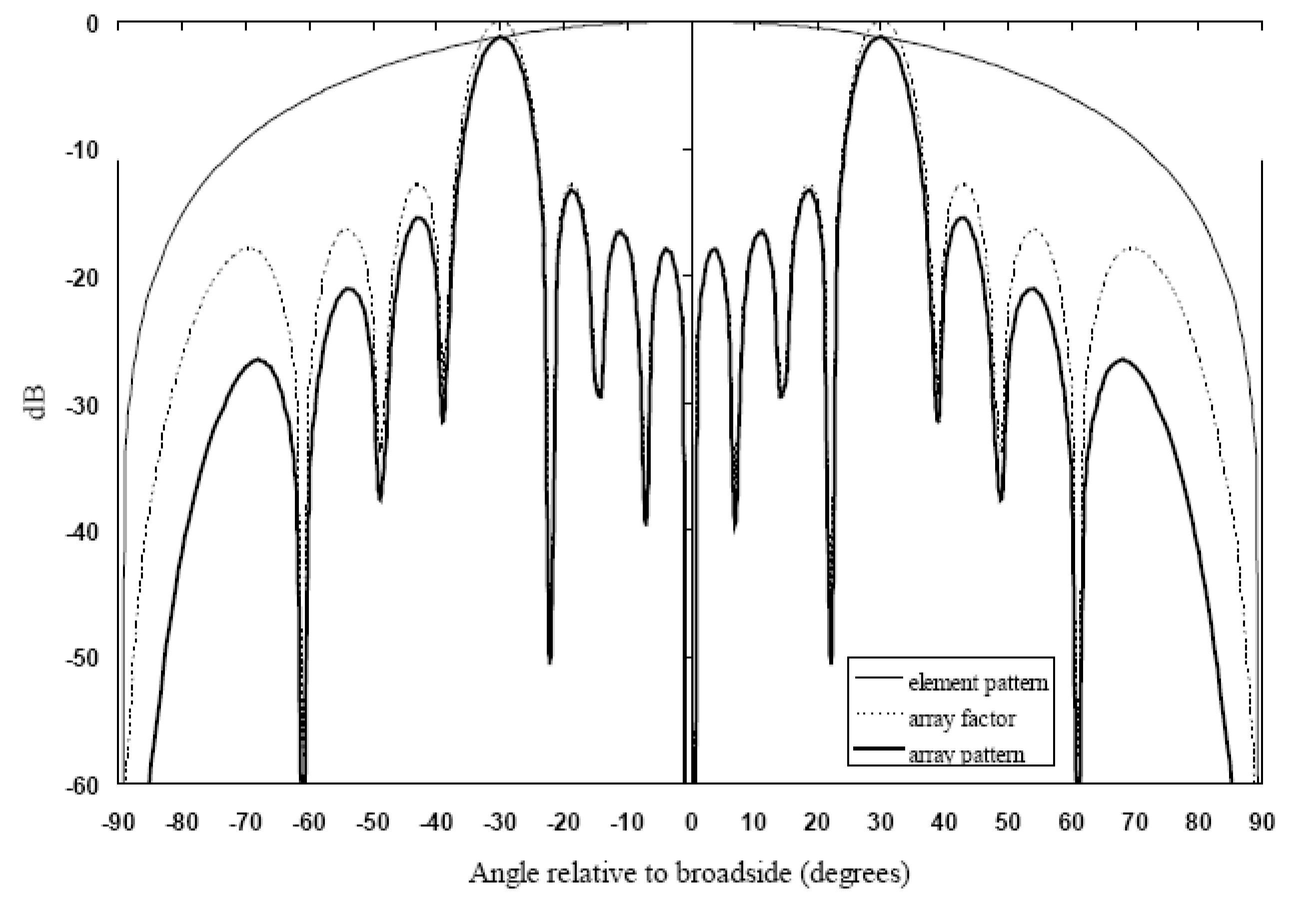
Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$; *beam pointing* $\theta_0=30^0$



Power radiation patterns of the element factor, the array factor and total array ($d=\lambda_0$) and *beam pointing* $\theta_0=30^0$

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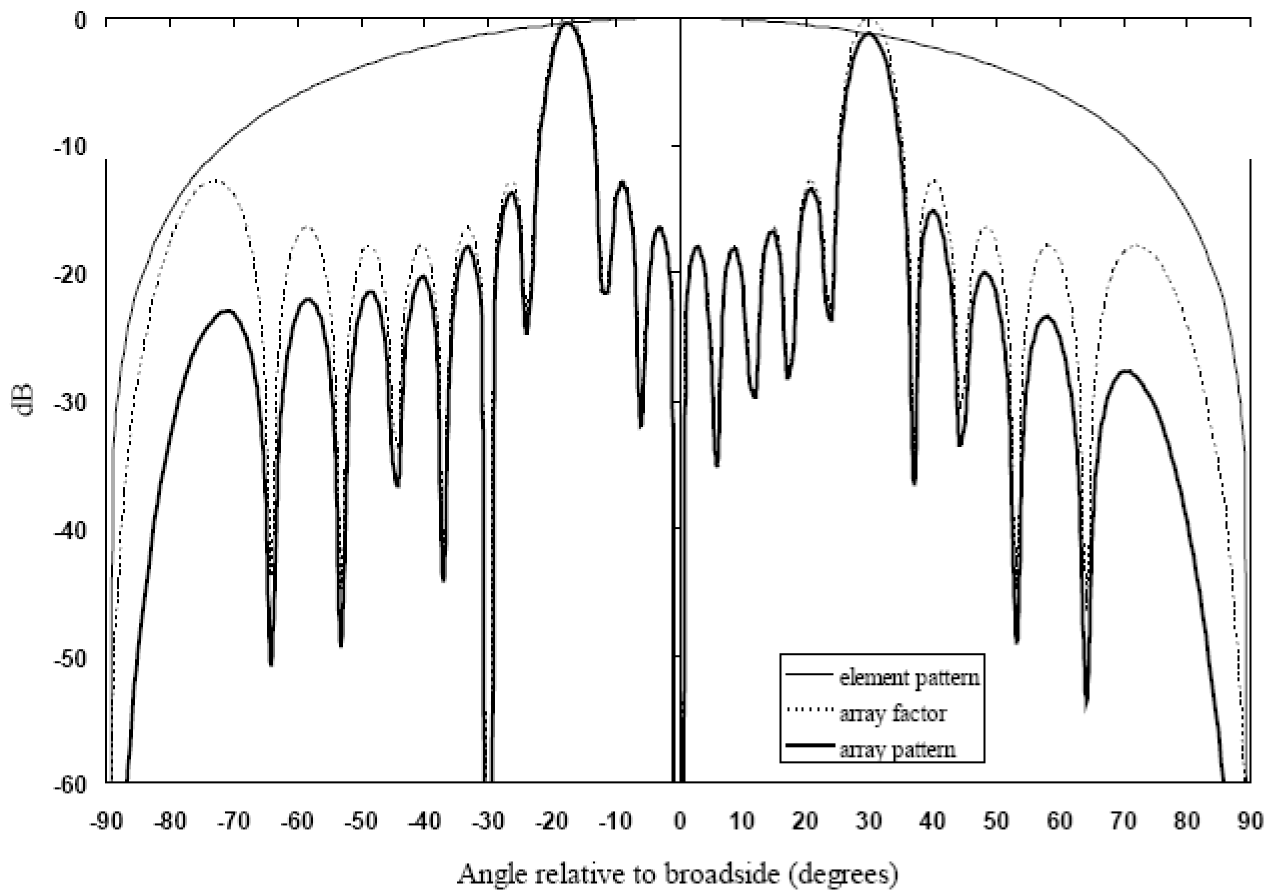
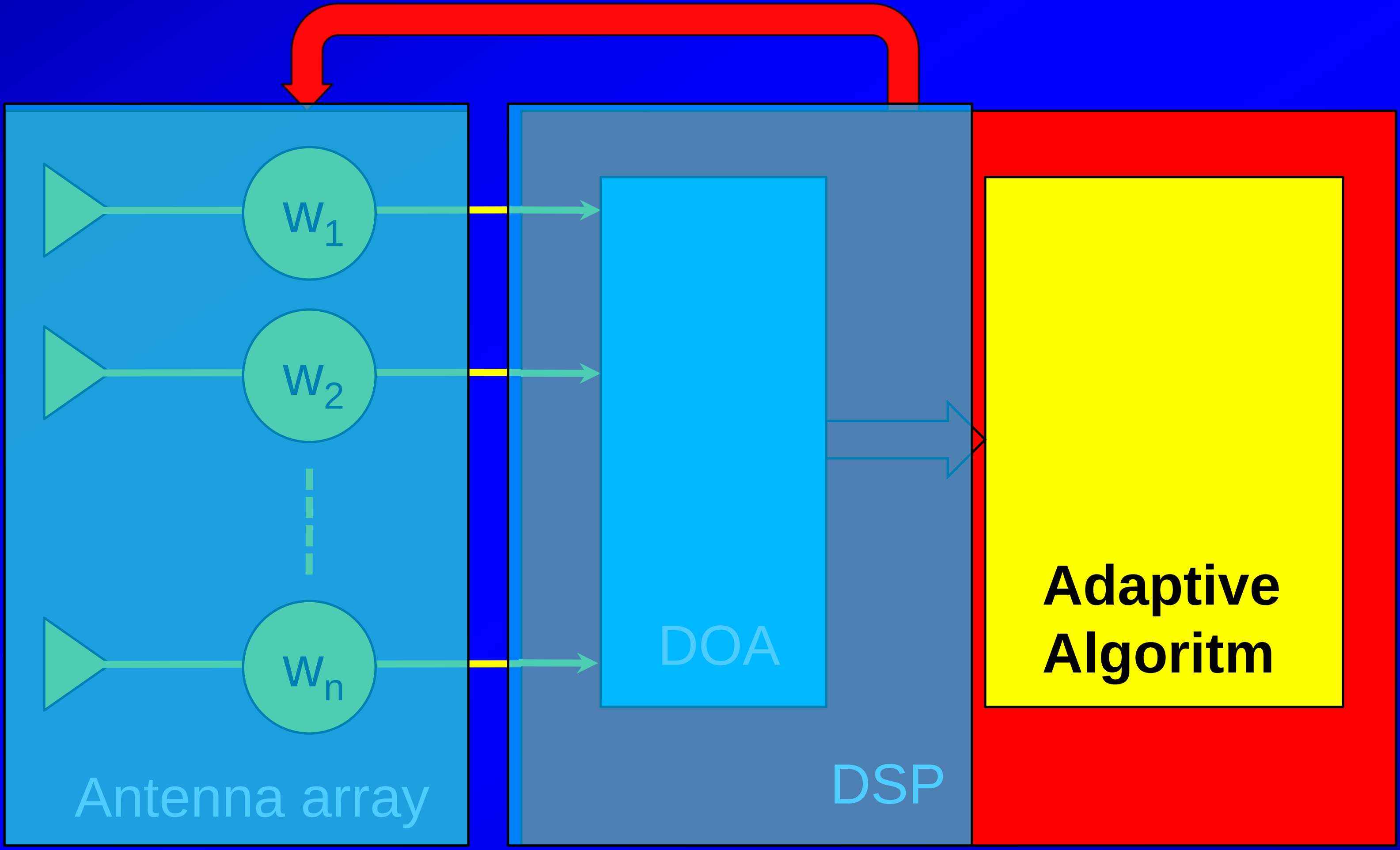
Example: Linear Array Antenna of eight elements for $d=\lambda_0/4$; $\lambda_0/2$; λ_0; $5\lambda_0/4$ and $S_e(\theta)=\cos\theta$; *beam pointing* $\theta_0=30^0$



Power radiation patterns of the element factor, the array factor and total array ($d=5\lambda_0/4$) and *beam pointing* $\theta_0=30^0$

Beamforming



DOA – direction of arrival; DSP – digital signal processor

Beamforming

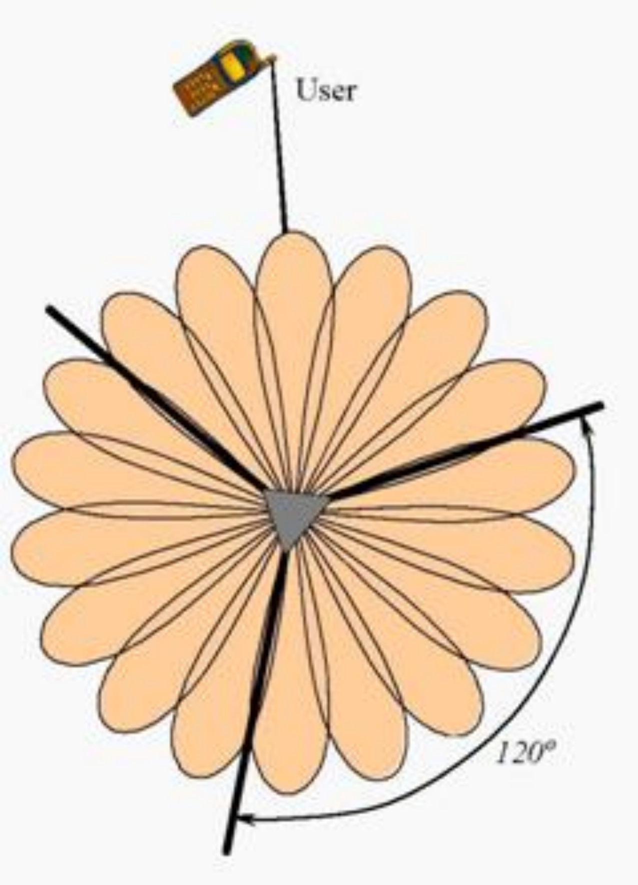
Smart Antenna Systems – by means of an internal feedback control, they can generate a customized radiation pattern to each remote user. In general, they form a main lobe toward a desired user and rejects interference outside the main lobe.

There are two types of systems:

1. ***Switched-Beam Systems***
2. ***Adaptive Antenna Systems***

Switched-Beam Systems

They use a number of fixed beams at the base station. The base station selects one of the predetermined fixed beam that provides the greatest output power for the desired user.



Advantages:
Cost – less complex and easier to retro-fit to existing wireless technologies

Disadvantages:
Lower Beam Resolution

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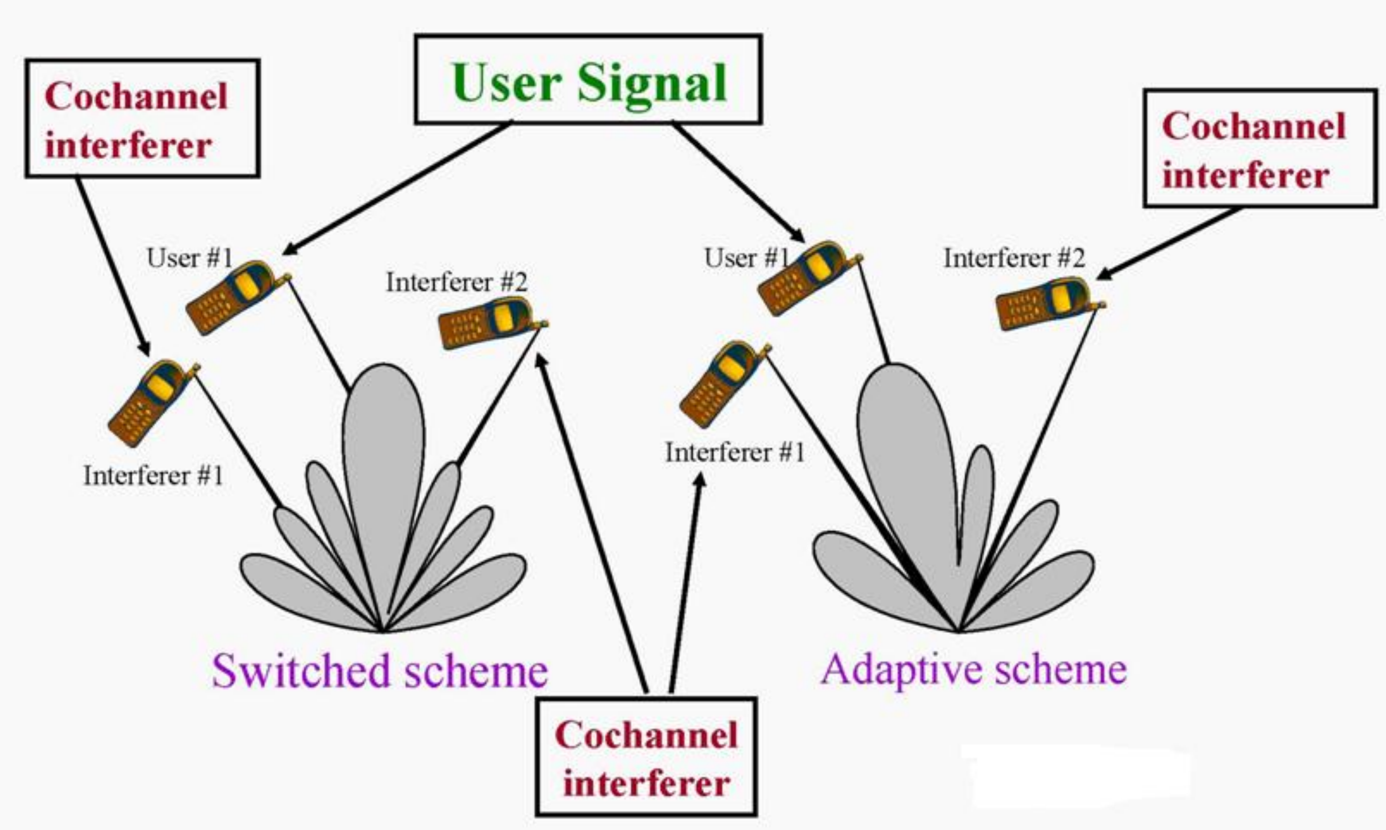
Switched vs. Adaptive Beamforming



Adaptive beamforming provides more degrees of freedom since they have the ability to adapt in real time the radiation pattern to the EM environment. It can direct the main beam toward the SOI while suppressing the antenna pattern in the direction of the interferes or SNOIs.

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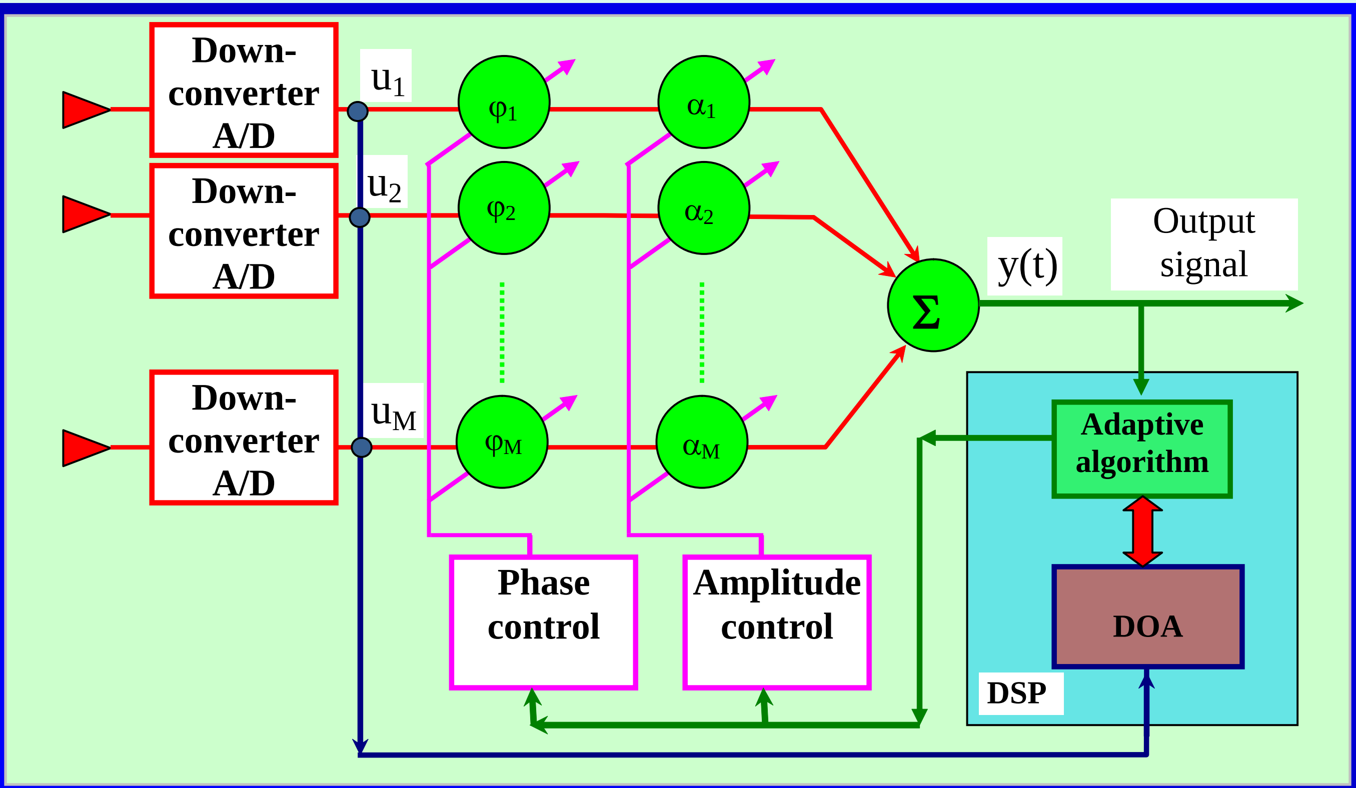
Functional Block Diagram of an Adaptive Array



1. Downconverting the received signals to baseband
2. Digitizing the signals
3. Locating the SOI using the DOA algorithms
4. Tracking continuously the SOI and NSOIs by dynamically changing the weights (amplitude and phases of the signals)

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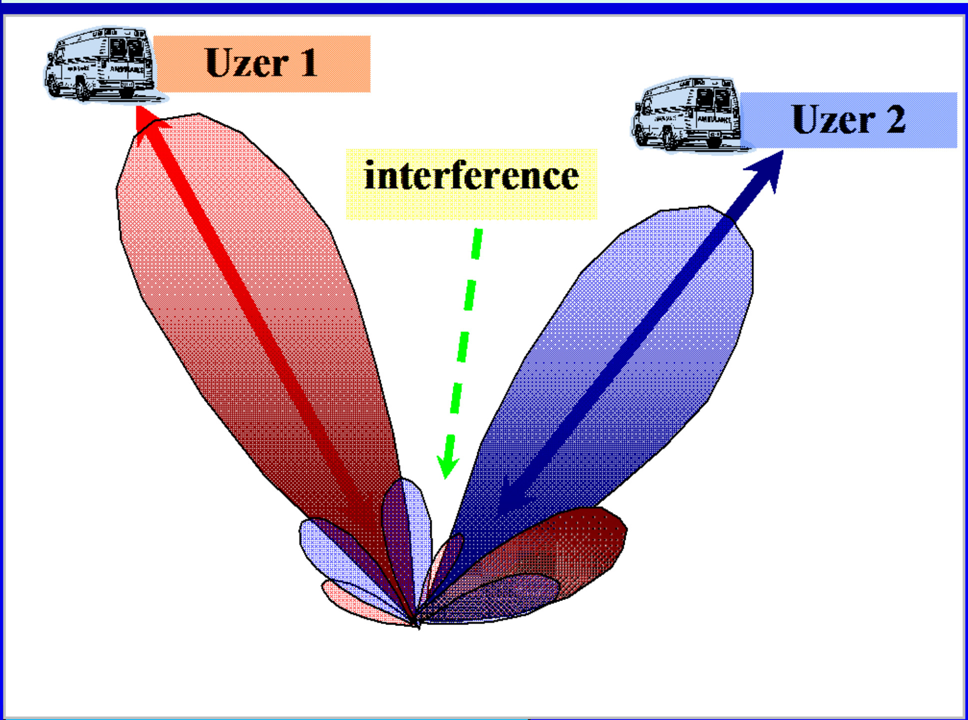
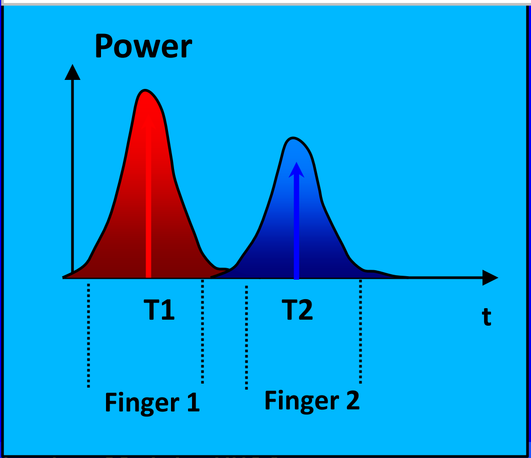
Spatial Division Multiple Access (SDMA)

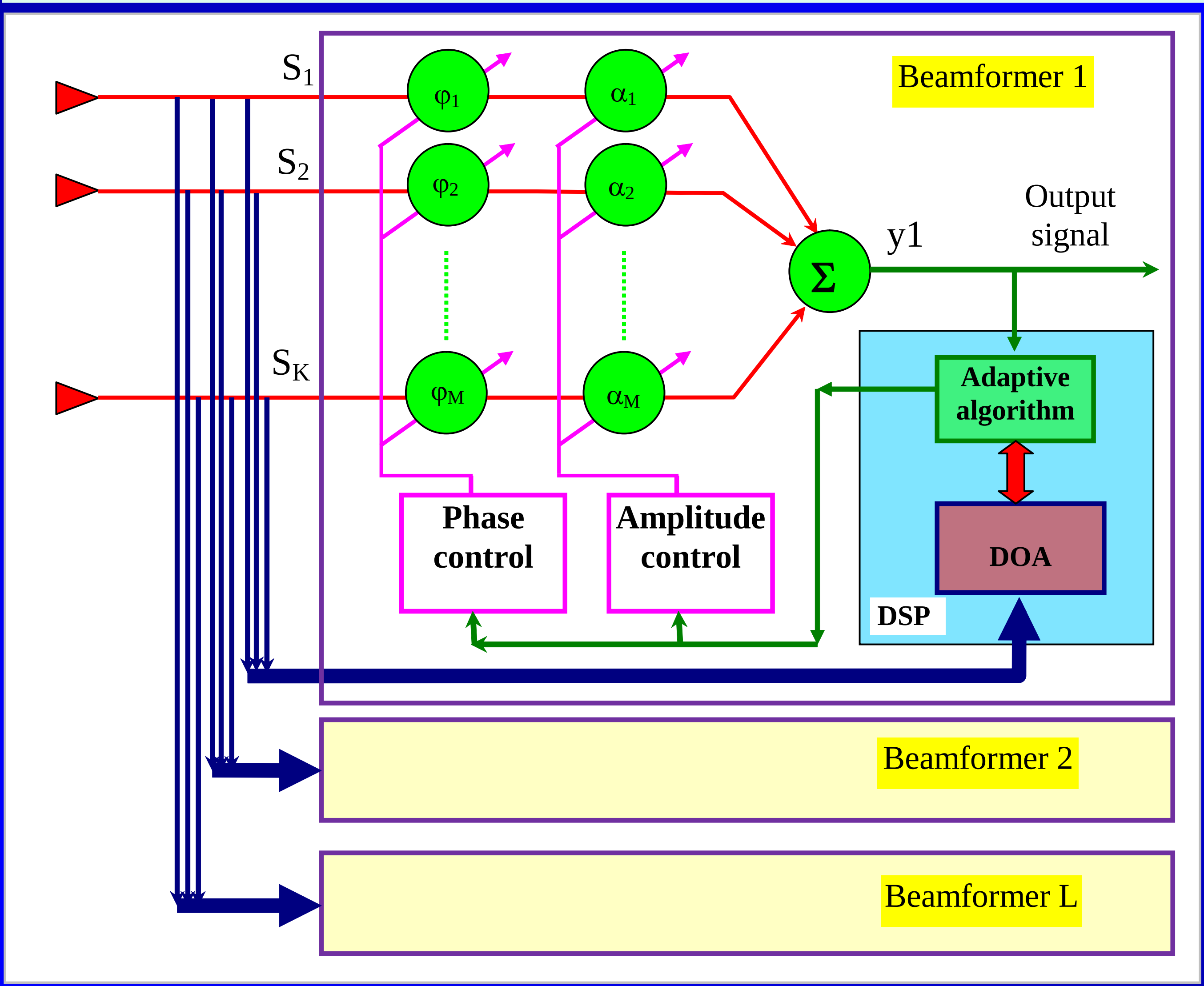


SDMA is among the most sophisticated utilization of smart array antenna technology.
Advance - spatial-processing capability enable it to locate many users, creating a different beam for each user.



More than one user can be allocated to the same physical communication channel in the same cell, simultaneously, with only an angle separation. Ideally, each beamformer creates a maximum toward each of its desired users while nulling the other users/interferes.

Spatial Division Multiple Access (SDMA)

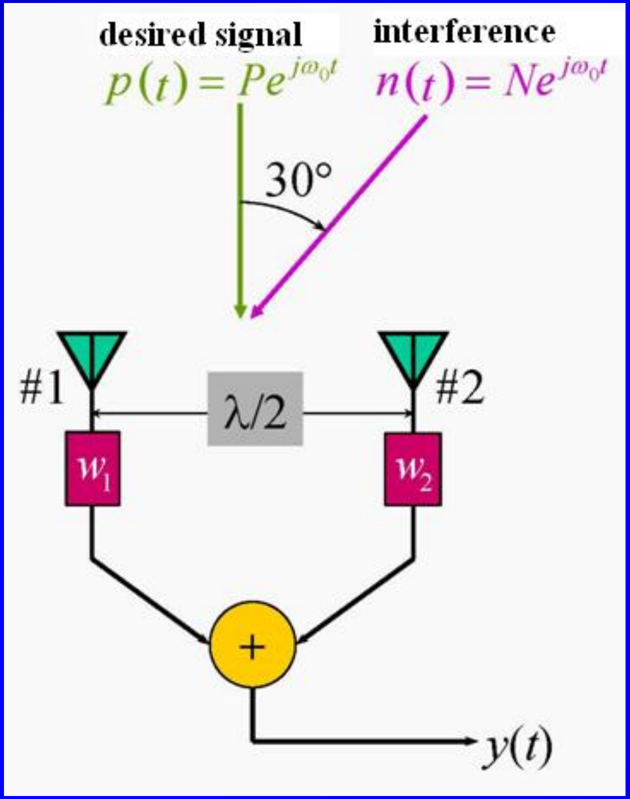


SDMA is accomplished by having L parallel beamformers at the base station operating independently, where each beamformer has its own adaptive algorithm to control its own set of weights and its own DOA algorithm to determine the time delay of each user's signal

Example: Adaptive Beamforming

Determine the complex weights of a two-element antenna array (d=λ/2) to:

1. receive a desired signal (SOI) toward broadside ($\theta_0=0^0$)
2. cancel an interference signal (SNOI) toward $\theta_1=30^0$



1. The output ***y(t)*** of the array due to the desired signal ***p(t)*** is:

$$y(t)=Pe^{j\omega_0 t}\left(w_1+w_2\right)$$

For the output ***y(t)*** to be equal only to the desired signal ***p(t),*** it is necessary that:

$$\left(w_1+w_2\right)=1$$

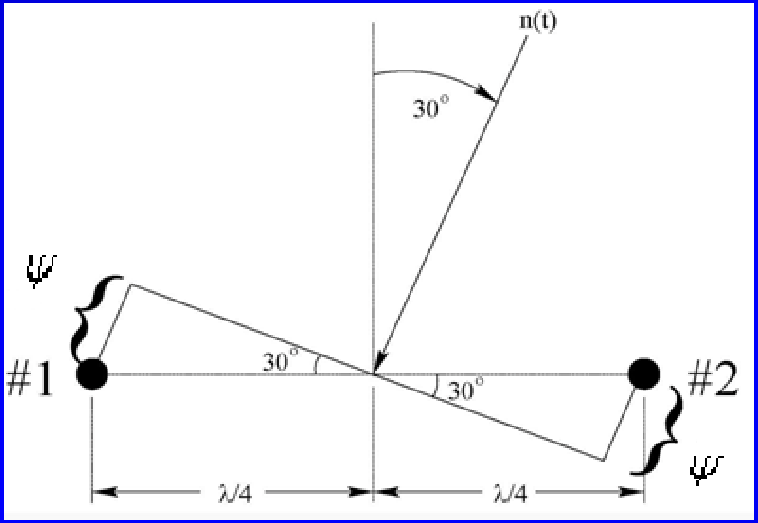
The elements of the array are assumed to be isotropic and the impinging signals are sinusoids. There is *no coupling between the elements*.

Example: Adaptive Beamforming

2. The output *y(t)* of the array due to the interfering signal *n(t)* is:

$$y(t) = Ne^{j(\omega_0 t-\pi/4)}w_1 + Ne^{j(\omega_0 t+\pi/4)}w_2$$

Where *ψ = ±π/4* is conected with the phase delay and lead, recpectively



$$\psi = k(d/2)\sin 30^0 = \pi/4$$

$$e^{j(\omega_0 t\pm\pi/4)} = \frac{e^{j\omega_0 t}}{\sqrt{2}}(1\pm j)$$

the output *y(t)* can be rewritten as:

$$y(t) = Ne^{j\omega_0 t}\left[\frac{\sqrt{2}}{2}(1-j)w_1 + \frac{\sqrt{2}}{2}(1+j)w_2\right]$$

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Example: Adaptive Beamforming

If we take into account that the output responce *y(t)* of the array due to the interfering signal *n(t)* has to be regected totally, it is necessary that:

$$\begin{cases} w_1 + w_2 = 1 \\ \dfrac{\sqrt{2}}{2}(1-j)w_1 + \dfrac{\sqrt{2}}{2}(1+j)w_2 = 0 \end{cases}$$

Solving simultaneosly the linear system of two complex equations for weight coefficients gives the SOLUTION:

$$\begin{cases} w_1 = \dfrac{1}{2} - j\dfrac{1}{2} \\ w_2 = \dfrac{1}{2} + j\dfrac{1}{2} \end{cases}$$

Optimal Beamforming Techniques

Adaptive beamforming can direct the main beam toward the SOI while suppressing the antenna pattern in the direction of the interferences or SNOIs.

The DSP computes the set of weights amplitude and phase in relation to the *adaptive algorithm* that optimizes a criterion or cost function.

The cost function is inversely associated with the quality of the signal at the array output, so that when the cost function is minimized, the quality of the signal is maximized at the array output.

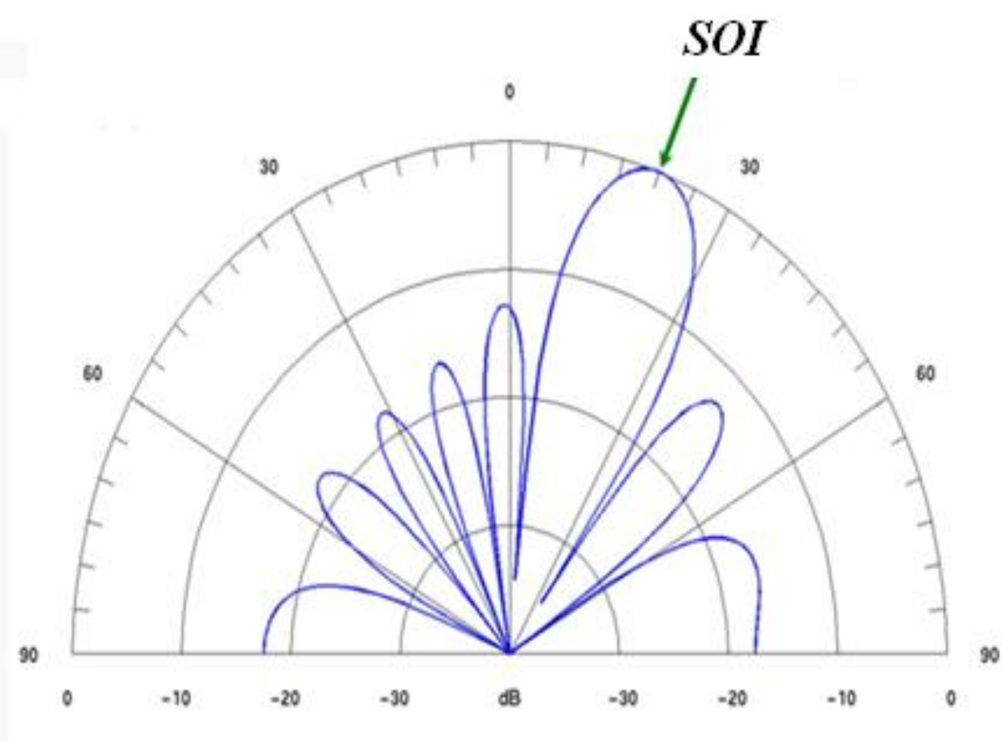
The most common optimal beamforming techniques are the:

1. **Maximum Signal-to-Noise Ratio (MSNR)**
2. **Minimum Mean Square Error (MMSE)**
3. **Minimum noise Variance (MV)**

Example: Adaptive Beamforming

Determine the complex weights (amplitude and phase) of the 8-isotropic elements linear array (d=λ/2) for assuming:

1. Receive a desired signal (SOI) toward $\theta_0 = 20^0$
2. There are no interference signals



	Classical		LMS (it=55)	
Element	|w|	Arg(w)	|w|	Arg(w)
1	1.0	0.0	1.0	0.0
2	1.0	-61.6	1.0	-61.6
3	1.0	-123.1	1.0	-123.1
4	1.0	-184.7	1.0	-184.7
5	1.0	-246.3	1.0	-246.3
6	1.0	-307.8	1.0	-307.8
7	1.0	-369.4	1.0	-369.4
8	1.0	-431.0	1.0	-431.0

Two methods lead to basically identical results in correspodning pattern and amplitude and phase excitation

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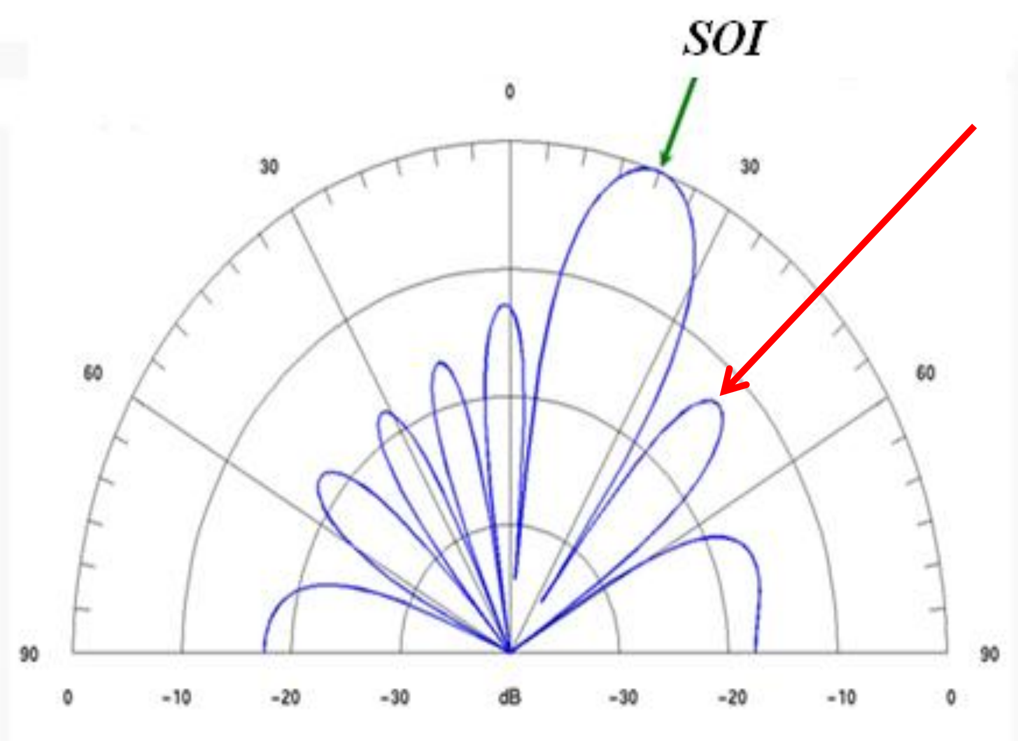
Example: Adaptive Beamforming

Determine the complex weights (amplitude and phase) of the 8-isotropic elements linear array ($d=\lambda/2$) for assuming:

1. Receive a desired signal (SOI) toward $\theta_0 = 20^0$
2. Cancel simultaneously an interference signal (SNOI) toward $\theta_i = 45^0$



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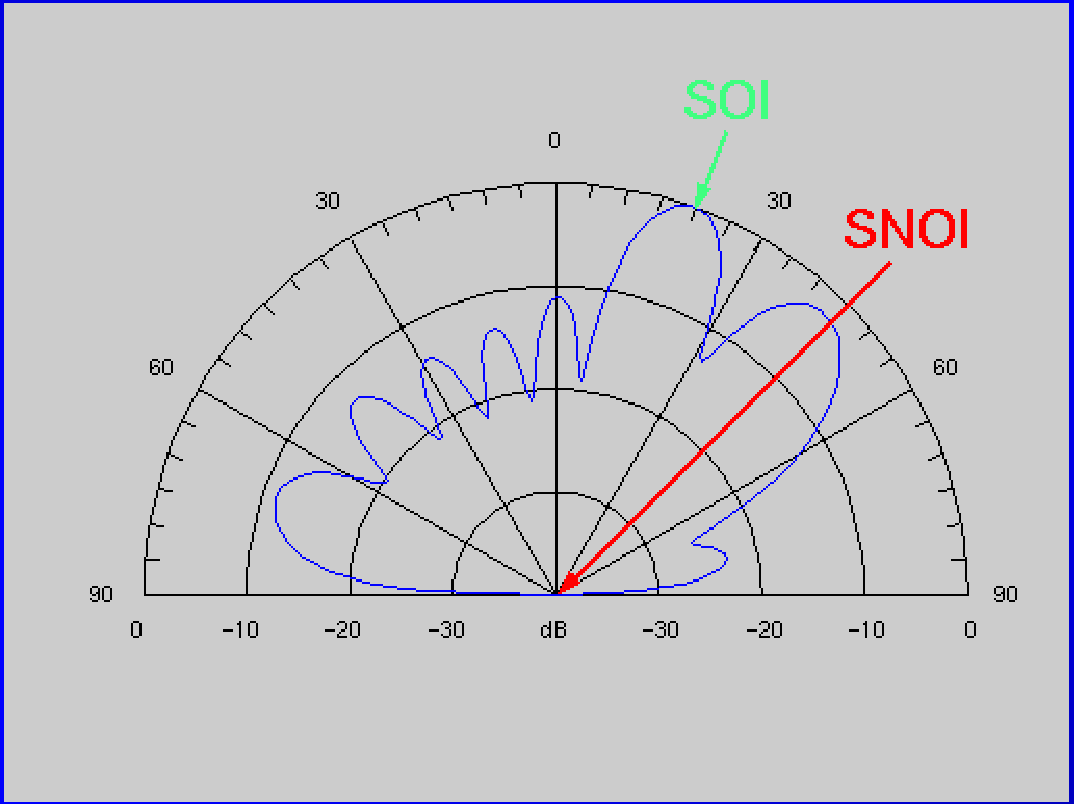
Example: Adaptive Beamforming

Determine the complex weights (amplitude and phase) of the 8-isotropic elements linear array (d=λ/2) for assuming:

1. **Receive a desired signal (SOI) toward $\theta_0 = 20^0$**
2. **Cancel simultaneously an interference signal (SNOI) toward $\theta_i = 45^0$**



LMS is used

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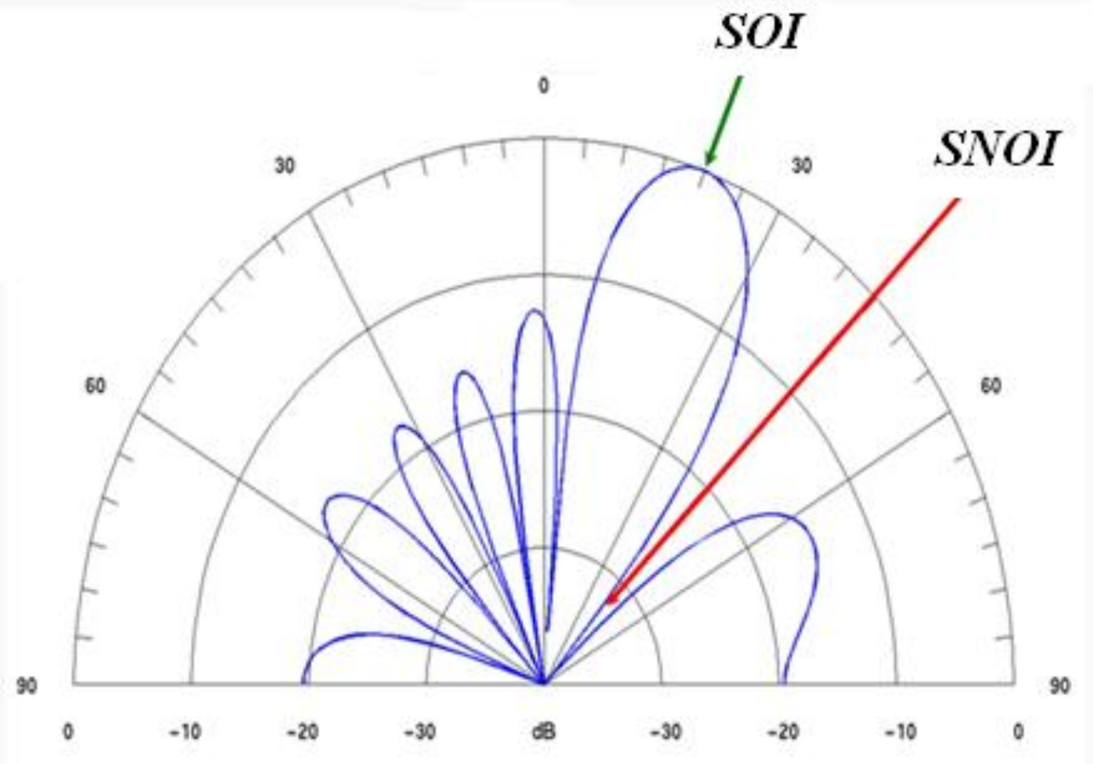
Example: Adaptive Beamforming

Determine the complex weights (amplitude and phase) of the 8-isotropic elements linear array (d=λ/2) for assuming:

1. **Receive a desired signal (SOI) toward $\theta_0 = 20^0$**
2. **Cancel simultaneously an interference signal (SNOI) toward $\theta_i = 45^0$**



	LMS (it=81, μ=0.01, stop <40dB)	
Element	*|w|*	*Arg(w)*
1	*1.0*	*-11.6*
2	*0.9*	*-57.1*
3	*1.14*	*-109.9*
4	*1.38*	*-178.8*
5	*1.38*	*-252.2*
6	*1.14*	*-321.0*
7	*0.9*	*-373.9*
8	*1.0*	*-419.4*

We cannot use the classical method.

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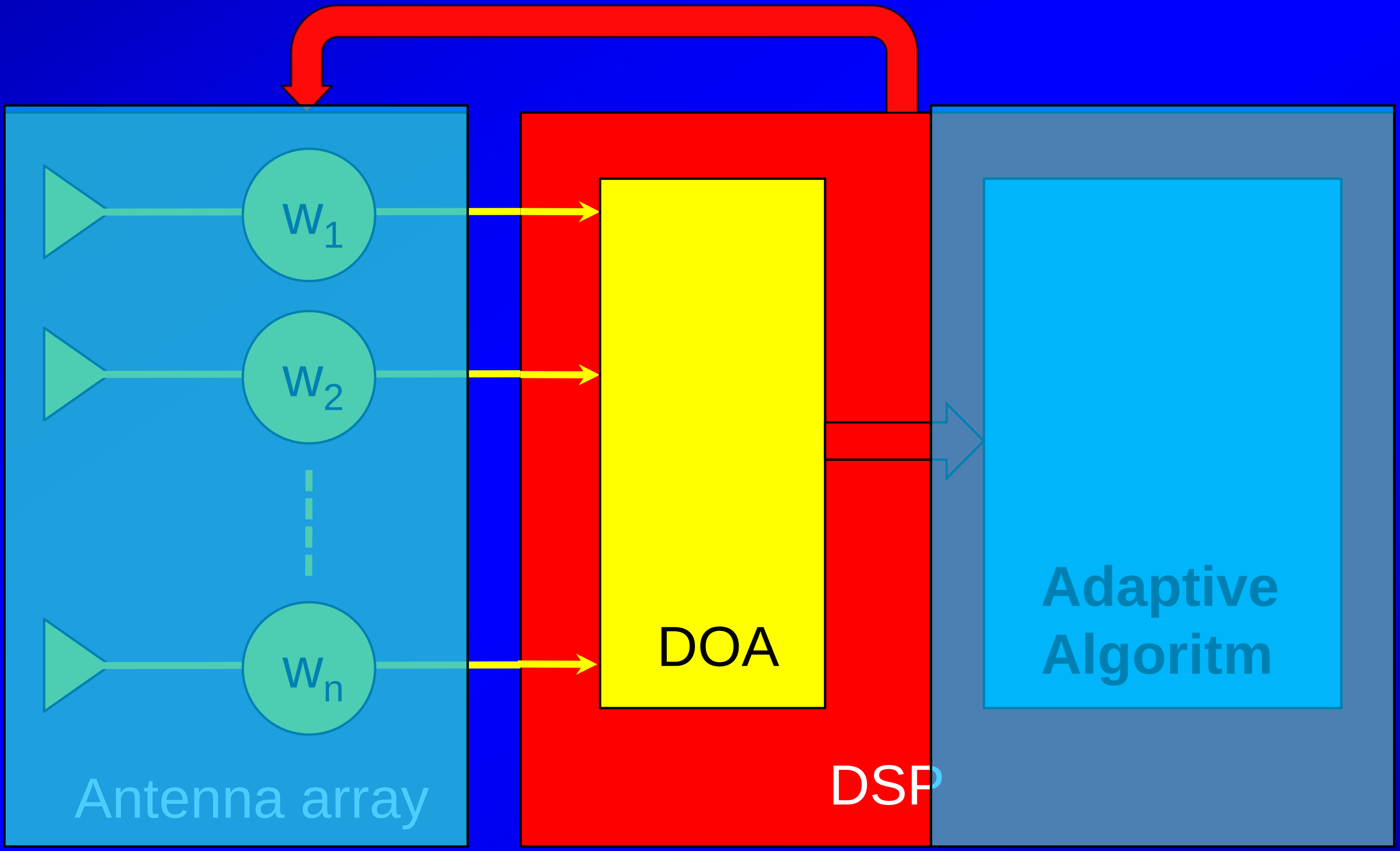
Direction-of-Arrival (DOA)



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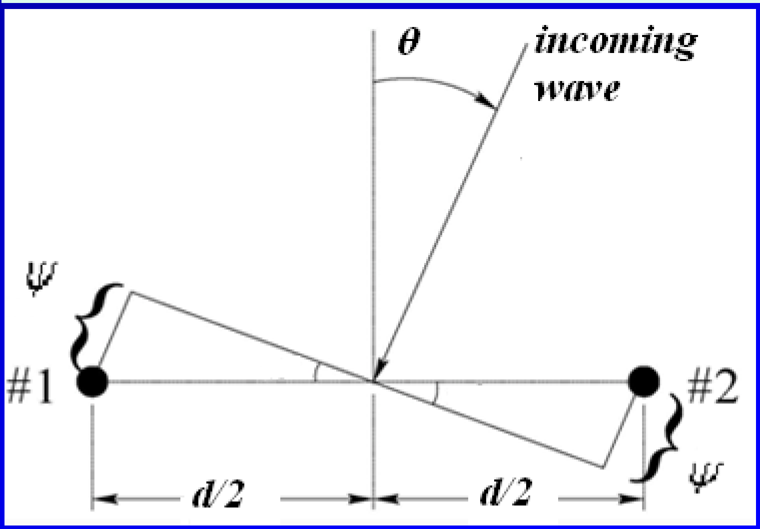
DOA. Time difference of arrival



$$\psi = k(d/2)\sin\theta^0 = \pi/4$$

When an incoming wave impinges with an angle ***θ*** on an antenna array, it produces time **delay** and **lead** relative to antenna centre, that depend on:

1. The antenna geometry
2. The spacing between the elements

$$\Delta t = (t_1 - t_2) = \frac{\Delta d}{v_0} = \frac{k(d/2)\sin\theta}{v_0}$$

$$\sin\theta = \frac{v_0}{d}\Delta t = \frac{v_0}{d}(t_1 - t_2)$$

$$\theta = \sin^{-1}\left(\frac{d}{v_0}\Delta t\right) = \sin^{-1}\left(\frac{d}{v_0}\sin^{-1}(t_1 - t_2)\right)$$

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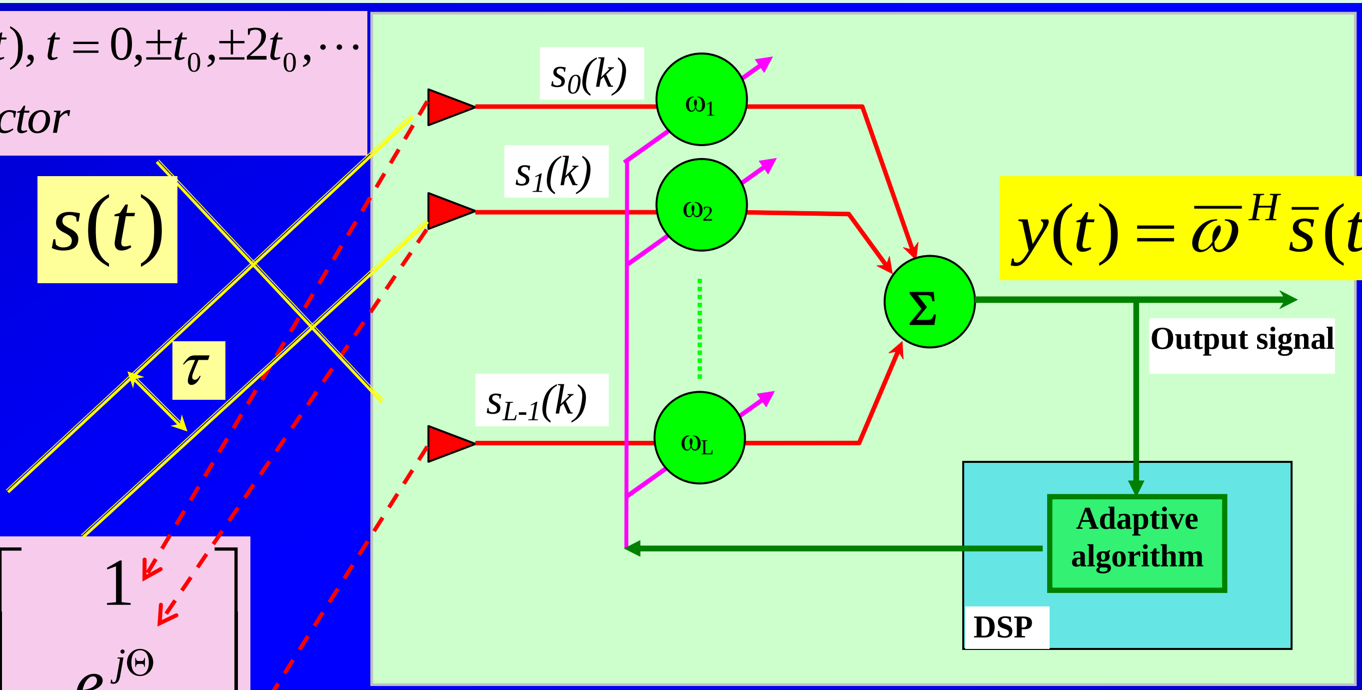
Adaptive Beamforming

$$\bar{s}(t)=\bar{\psi}(t)s(t),\ t=0,\pm t_0,\pm 2t_0,\cdots$$

wavefront vector



$$y(t)=\bar{\omega}^H\bar{s}(t)$$

$$\bar{\psi}(\theta)=\begin{bmatrix}1\\ e^{j\Theta}\\ \vdots\\ e^{j(L-1)\Theta}\end{bmatrix}$$

steering vector

$$\Theta=2\pi f\tau=\frac{2\pi d}{\lambda}\sin\theta$$

Output power

$$P=\sum_{n=0}^{N-1}\left|\bar{\omega}^H\bar{s}(nt_0)\right|^2=\bar{\omega}^H R\bar{\omega}$$

Measurement covariance

$$R=\frac{1}{N}\sum_{n=0}^{N-1}\bar{s}(nt_0)\bar{s}^H(nt_0)$$

DOA. Bartlett beamformer

$$\bar{s}(t) = \bar{\psi}(t)s(t),\ t = 0, \pm t_0, \pm 2t_0, \cdots$$

wavefront vector

Matched Filtering

$$\bar{\varpi} = \bar{\psi}(\theta)$$

$$y(t) = \bar{\varpi}^H \bar{s}(t)$$

$$P = \sum_{n=0}^{N-1} \left| \bar{\varpi}^H \bar{s}(nt_0) \right|^2 = \bar{\varpi}^H R \bar{\varpi} = \bar{\psi}^H(\theta) R \bar{\psi}(\theta)$$

Estimates the signal power

Bartlett beamformer properties:

1. **Very simple**
2. **Low resolution**
3. **High sidelobes**
4. **Good interference suppresion**

$$\Delta\theta = \arcsin \frac{\lambda}{L \cdot d}$$

DOA. Capon beamformer

(MVDR – Minimum Variance Distortionless Response)

$$\min P = \overline{\omega}^H R \overline{\omega} \quad u.c. \quad \overline{\omega}^H \overline{\psi} = 1$$

Solution:

$$\overline{\omega} = \frac{R^{-1}\overline{\psi}}{\overline{\psi}^H R^{-1} \overline{\psi}} \quad and \quad P = \frac{1}{\overline{\psi}^H R^{-1} \overline{\psi}}$$

Capon beamformer properties:

1. **High resolution**
2. **Low sidelobes**
3. **Good interference suppresion**
4. **Simetimes it can not handle – when the direction vector is not perfectly known (e.g. multipath, random scattering, array perturbations)**

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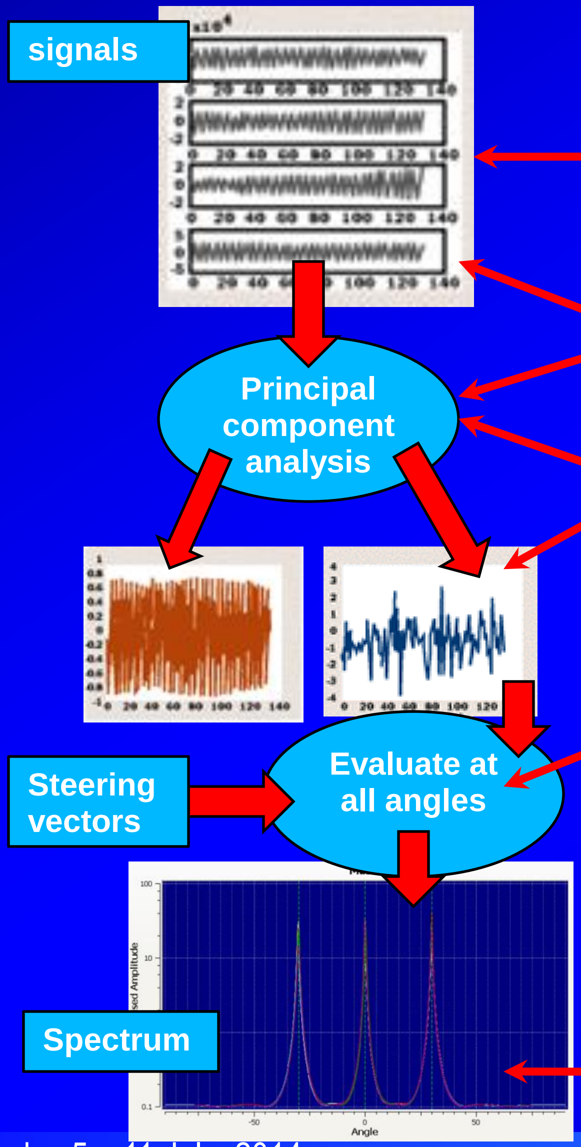
MUSIC Algorithm
(Superresolution, Multiple Signal Classification)


signals

Principal component analysis

Steering vectors

Evaluate at all angles

Spectrum

The MUSIC algorithm is one of the most researched DOA algorithms.

1. The input signals provide information about the DOA of the received plane waves as well as the noise received at each element. Using the algorithm, one can obtain multiple delayed versions of the plane waves and the antenna array geometry.

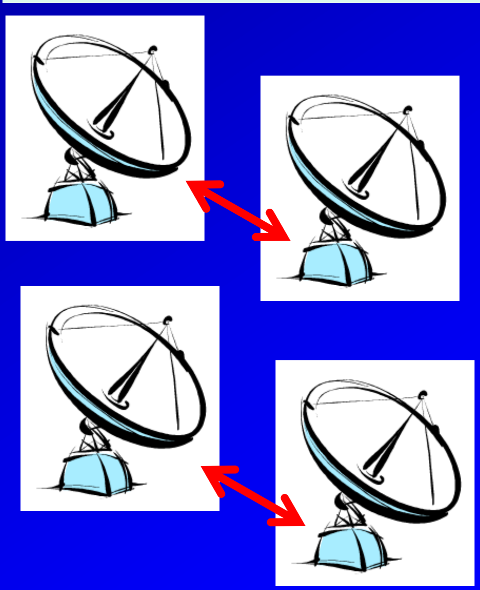
2. This makes it possible to exploit the spatial and temporal correlation between the different received signals to determine the angles of arrival.

3. The concept of the MUSIC algorithm is that the Eigenvectors can be divided into two subsets, one providing information about the correlated plane waves (signal space) and the other containing information derived from the uncorrelated noise (noise space).

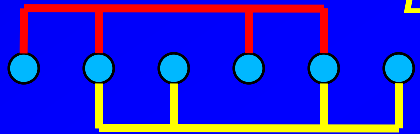
4. The Eigenvectors in the noise space are orthogonal to those in the signal space. As the signal space contains information about the angles of arrival from each plane wave, the steering vectors from those angles are also orthogonal to the vectors in the noise space. The magnitude of the product between a steering vector from a plane wave's DOA and the noise-space matrix is zero. The inverse of the magnitude of the product between a steering vector from all possible angles and the noise-space matrix is known as the *MUSIC spectrum*.

ESPRIT Algorithm

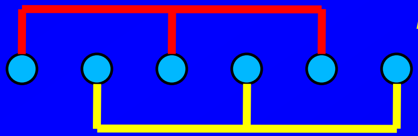
(Estimation of Signal Parameters via Rotational Invariance Technique)



It needs the sensor dublets



L=6, l=5



L=6, l=3

Advantages:

1. **Significant in computer speed and storage requirements for ESPRIT as compared with MUSIC.**
2. **Ability to work without array calibration**

Disadvantages:

1. **The array design must be such that the „pairwise identical” condition is satisfied**
2. **The effective halving of the number of array elements by combining them into doubles reduces the maximum number of rays that can be resolved**
3. **The angles of arrival are determined from phase shifts for a comparatively small displacement of less than wavelength**
4. **A planar array determines cone angle relative to the displacement vector, rather than azimuth and elevation angles separately**

***No spectrum*.**

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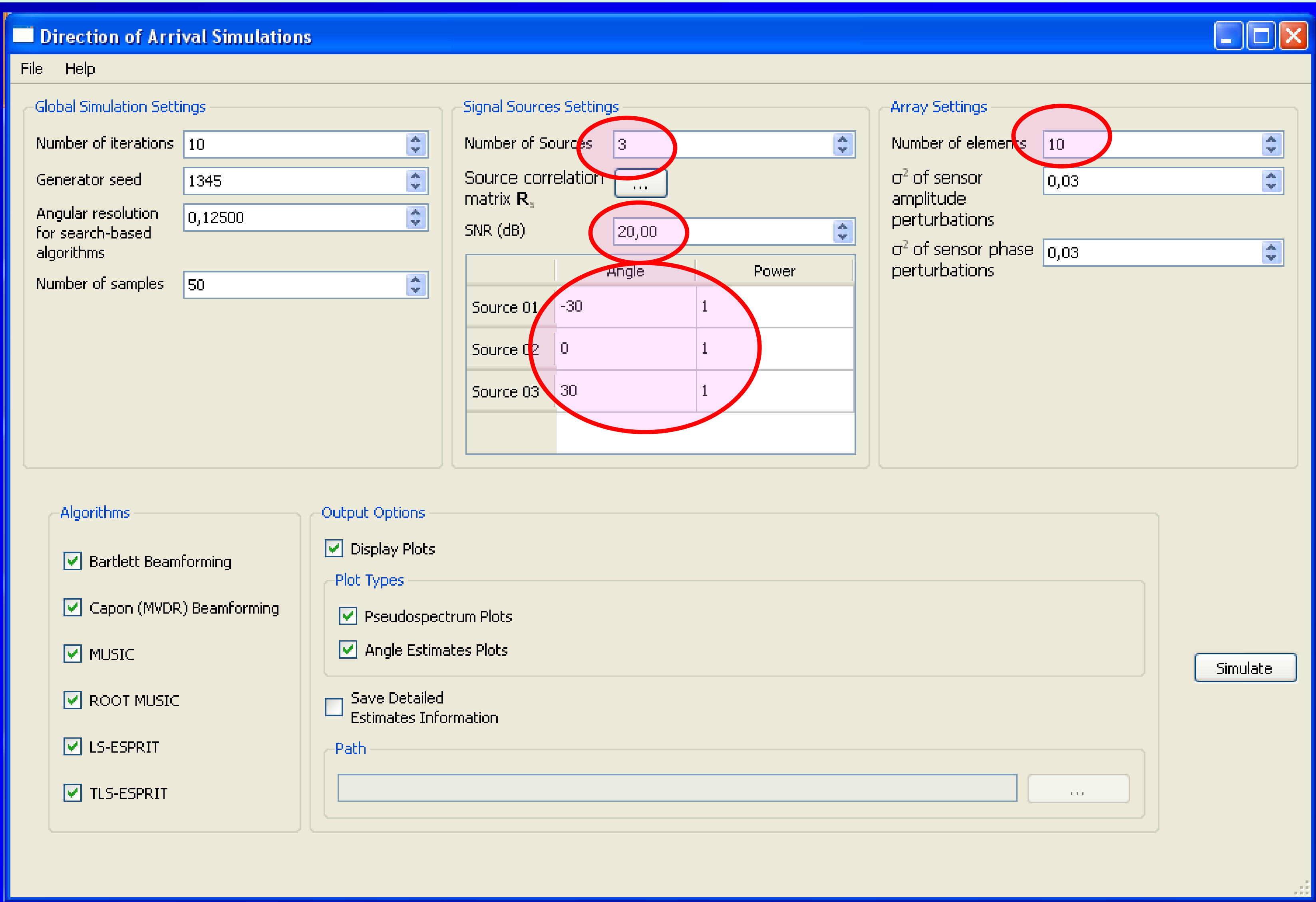
Number of elements – 10; Number of sources – 3; -30; 0; 30. SNR = 20 dB



Global Simulation Settings

Number of iterations: 10

Generator seed: 1345

Angular resolution for search-based algorithms: 0,12500

Number of samples: 50

Signal Sources Settings

Number of Sources: 3

Source correlation matrix $\mathbf{R}_s$: ...

SNR (dB): 20,00

	Angle	Power
Source 01	-30	1
Source 02	0	1
Source 03	30	1

Array Settings

Number of elements: 10

σ^2 of sensor amplitude perturbations: 0,03

σ^2 of sensor phase perturbations: 0,03

Algorithms

☑ Bartlett Beamforming

☑ Capon (MVDR) Beamforming

☑ MUSIC

☑ ROOT MUSIC

☑ LS-ESPRIT

☑ TLS-ESPRIT

Output Options

☑ Display Plots

Plot Types

☑ Pseudospectrum Plots

☑ Angle Estimates Plots

☐ Save Detailed Estimates Information

Path

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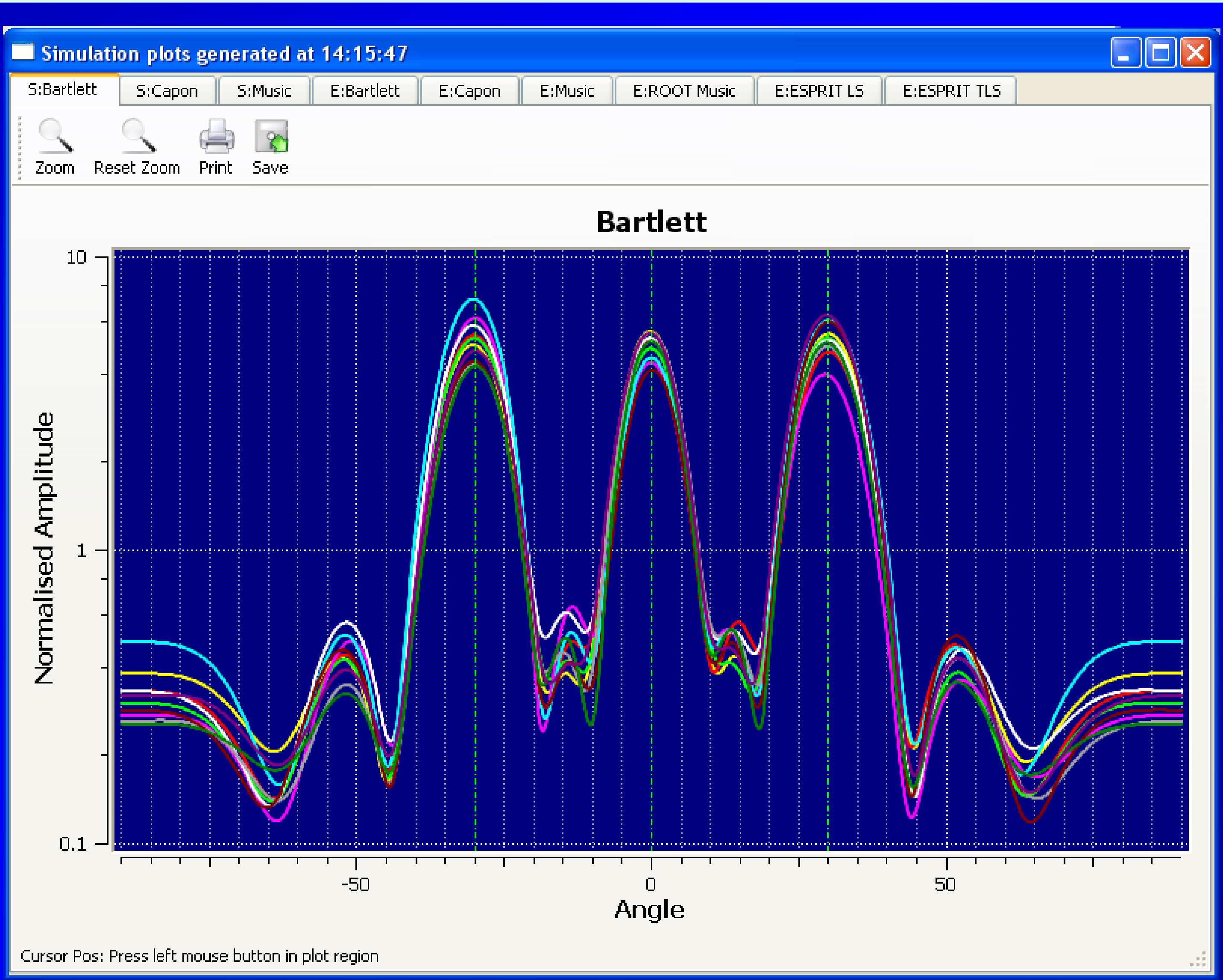
Number of elements – 10; Number of sources – 3; -30; 0; 30. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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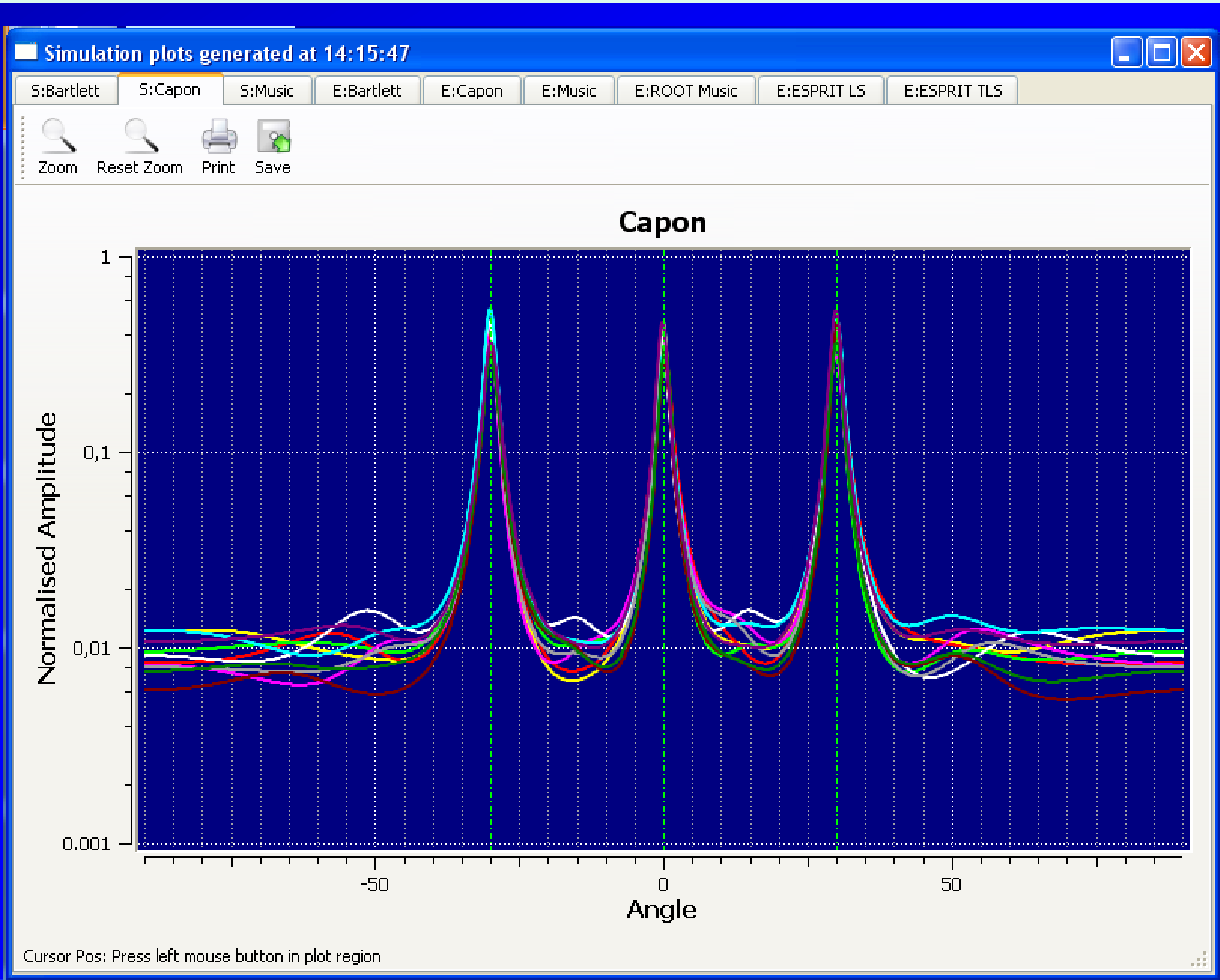
Number of elements – 10; Number of sources – 3; -30; 0; 30. SNR = 20 dB



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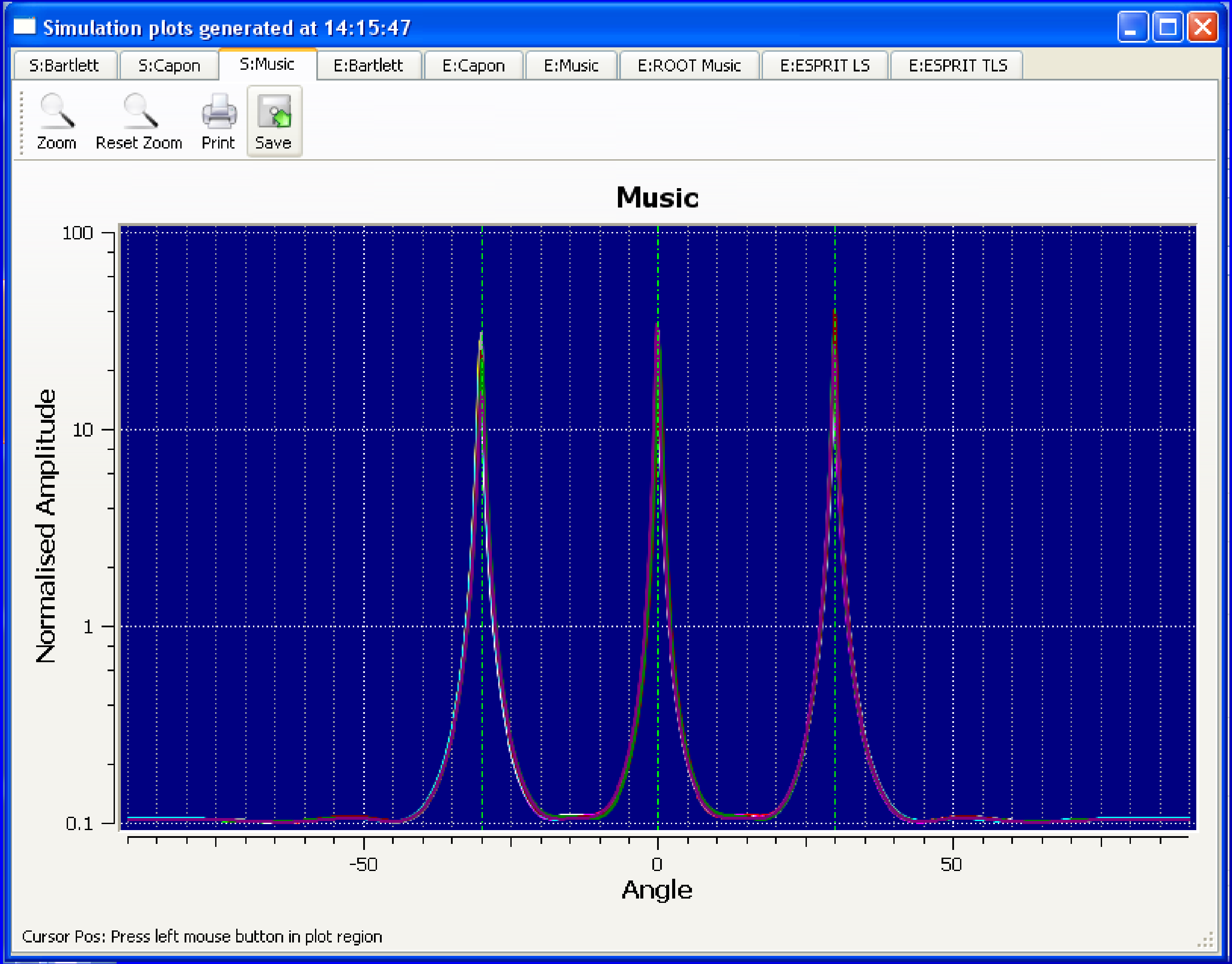
Number of elements – 10; Number of sources – 3; -30; 0; 30. SNR = 20 dB



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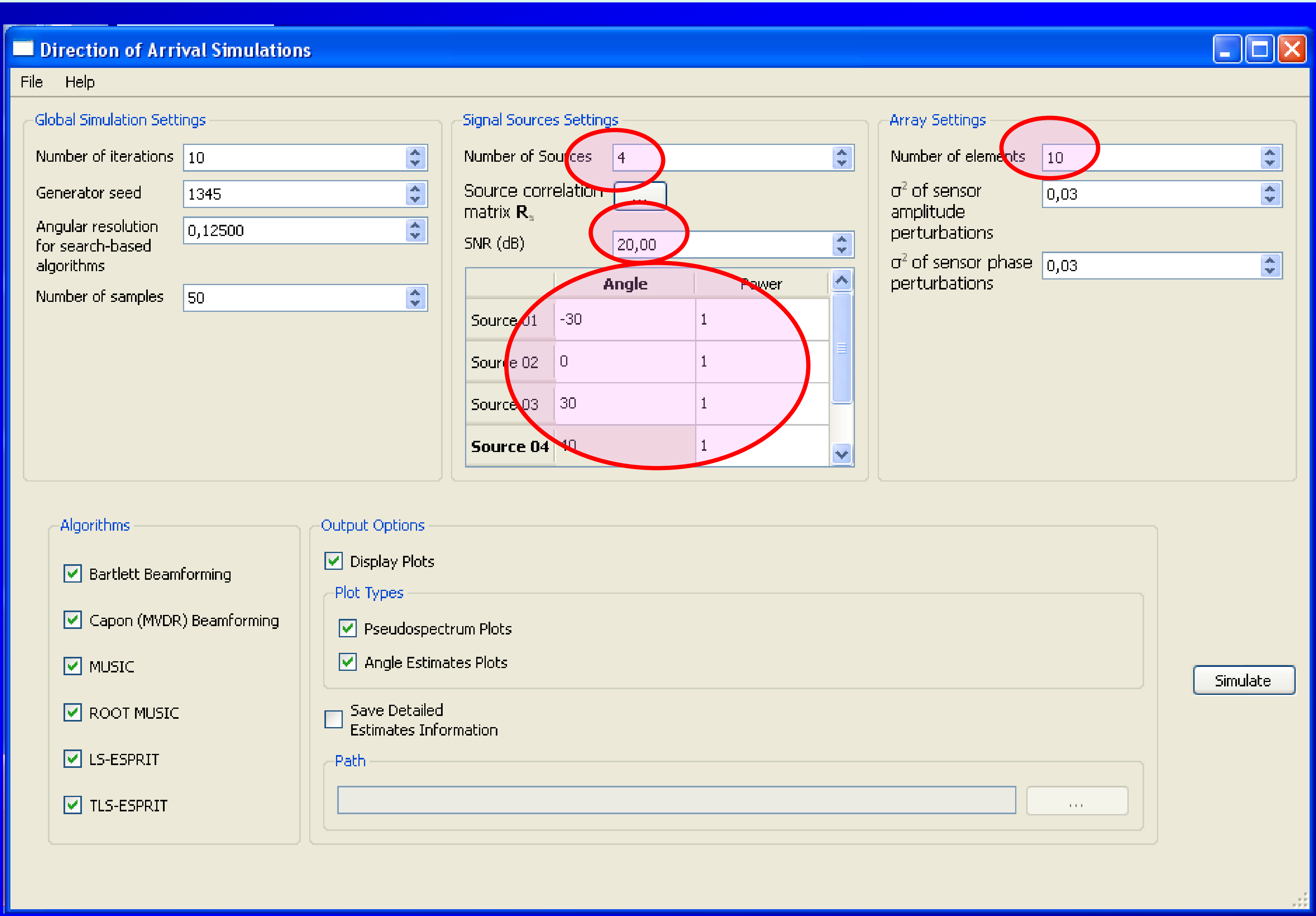
Number of elements – 10; Number of sources – 4; -30; 0; 30; 40. SNR = 20 dB



Global Simulation Settings

Number of iterations: 10

Generator seed: 1345

Angular resolution for search-based algorithms: 0,12500

Number of samples: 50

Signal Sources Settings

Number of Sources: 4

Source correlation matrix $\mathbf{R}_s$: ...

SNR (dB): 20,00

	Angle	Power
Source 01	-30	1
Source 02	0	1
Source 03	30	1
Source 04	40	1

Array Settings

Number of elements: 10

σ^2 of sensor amplitude perturbations: 0,03

σ^2 of sensor phase perturbations: 0,03

Algorithms

- ☑ Bartlett Beamforming
- ☑ Capon (MVDR) Beamforming
- ☑ MUSIC
- ☑ ROOT MUSIC
- ☑ LS-ESPRIT
- ☑ TLS-ESPRIT

Output Options

- ☑ Display Plots

Plot Types

- ☑ Pseudospectrum Plots
- ☑ Angle Estimates Plots

- ☐ Save Detailed Estimates Information

Path

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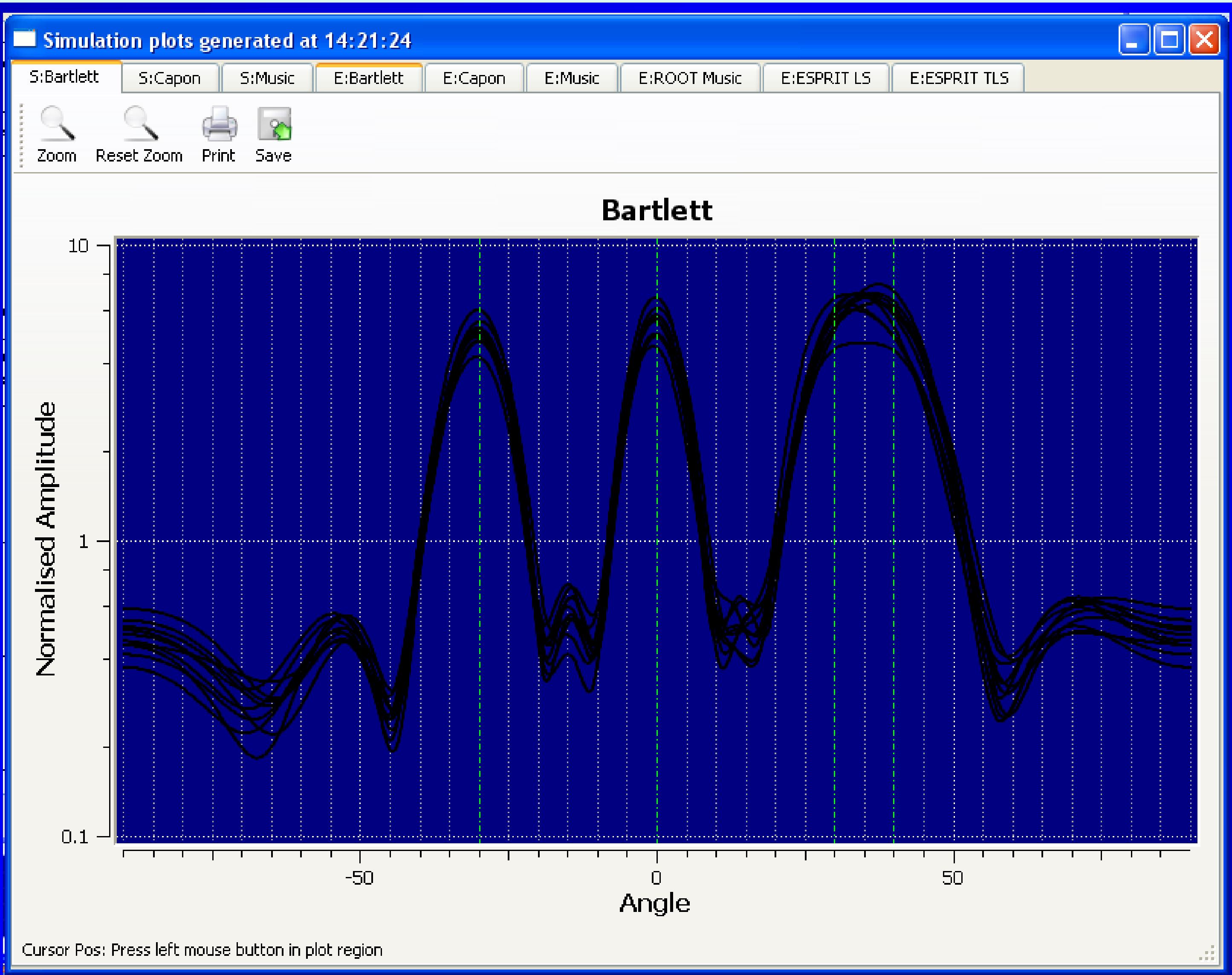
Number of elements – 10; Number of sources – 4; -30; 0; 30; 40. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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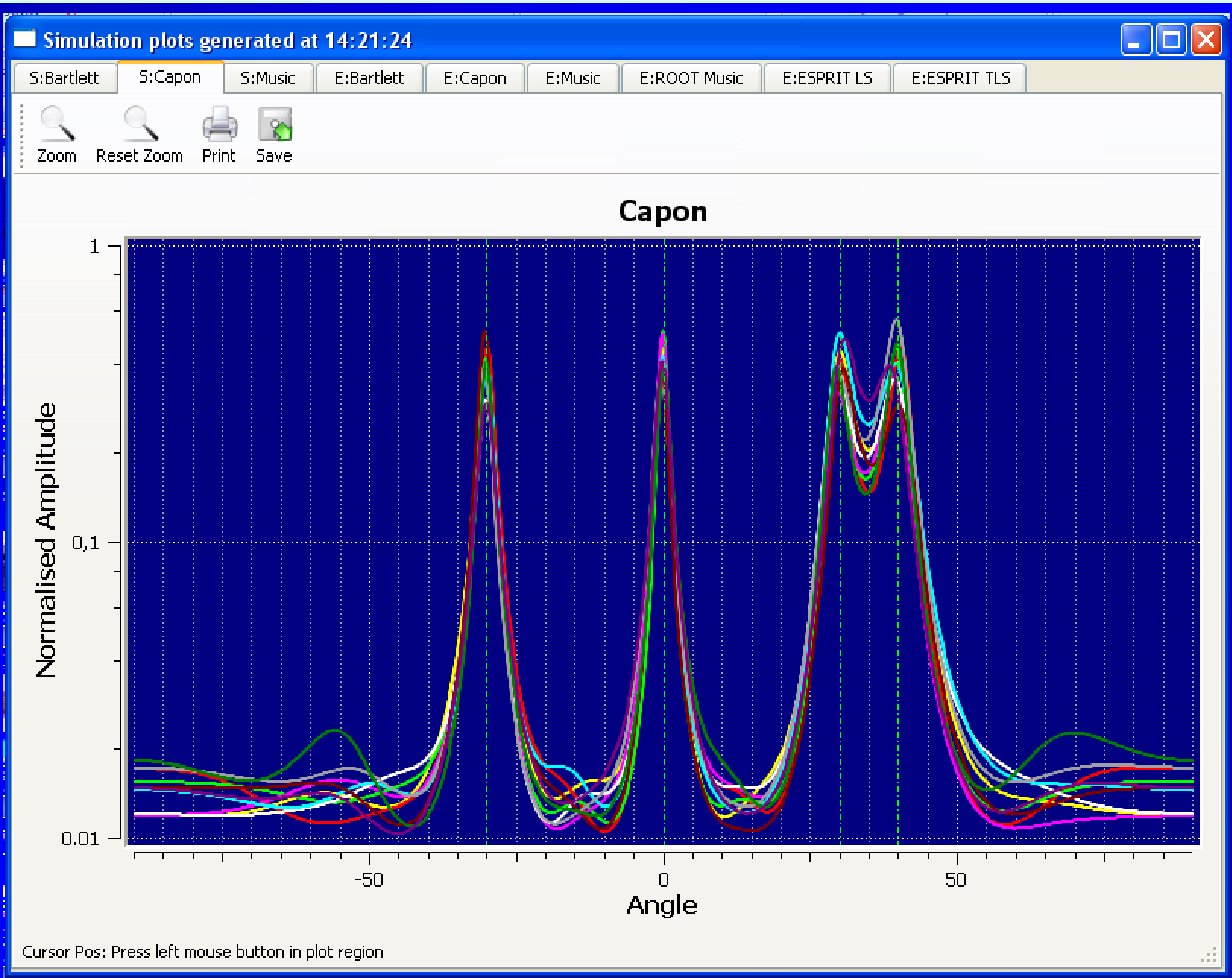
Number of elements – 10; Number of sources – 4; -30; 0; 30; 40. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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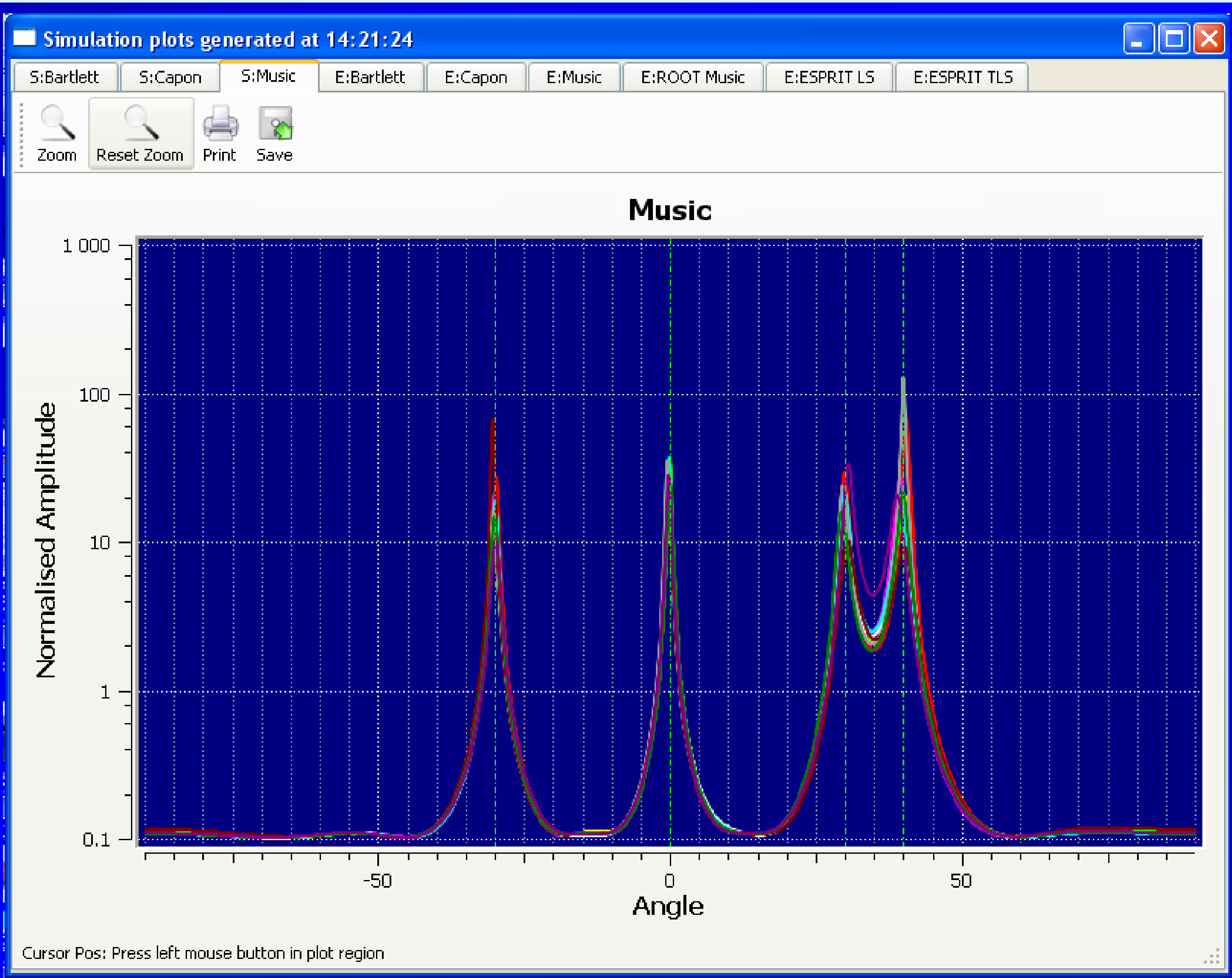
Number of elements – 10; Number of sources – 4; -30; 0; 30; 40. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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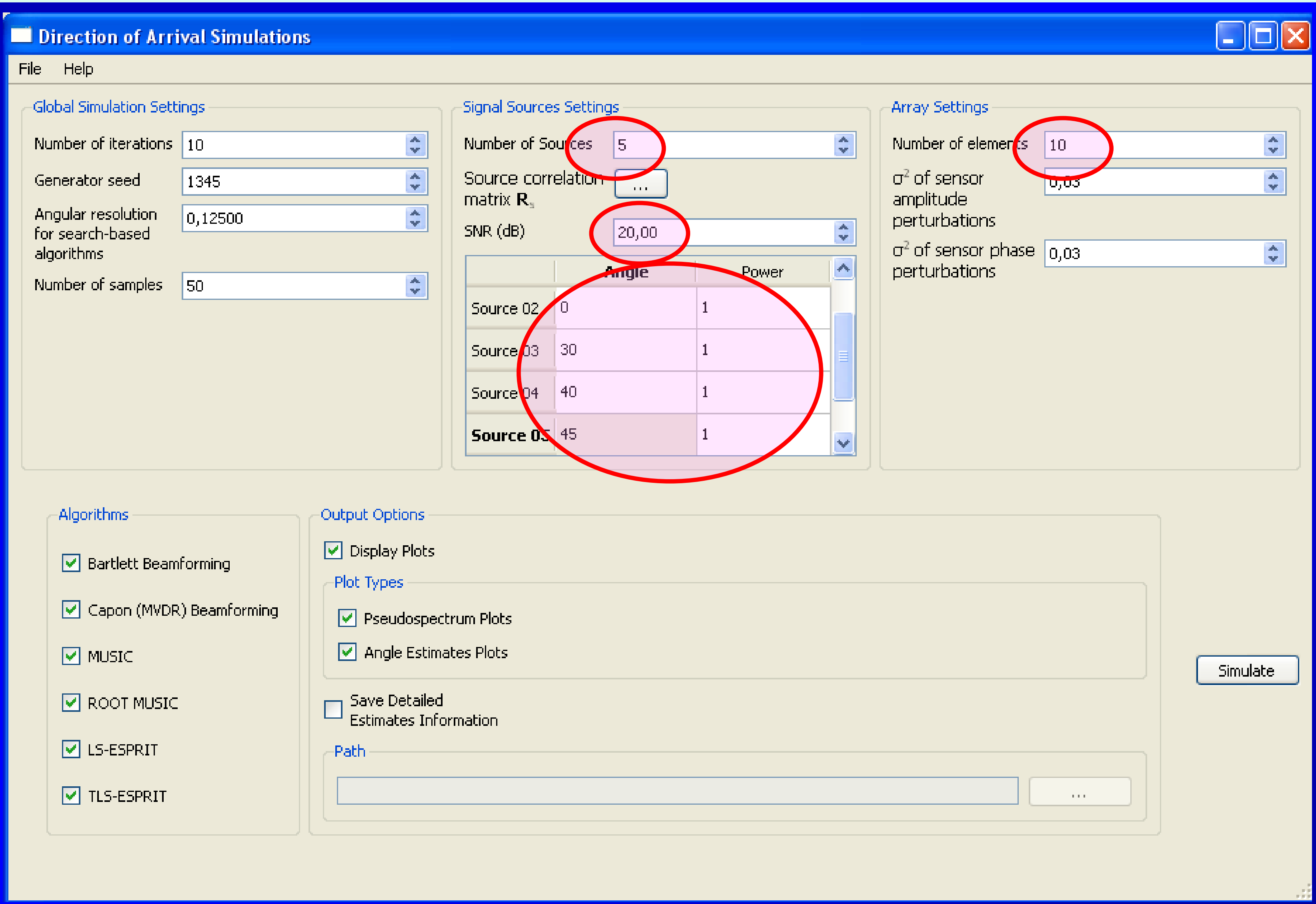
Number of elements – 10; Number of sources – 5; -30; 0; 30; 40; 45. SNR = 20 dB



Global Simulation Settings

Number of iterations: 10

Generator seed: 1345

Angular resolution for search-based algorithms: 0,12500

Number of samples: 50

Signal Sources Settings

Number of Sources: 5

Source correlation matrix $\mathbf{R}_s$: ...

SNR (dB): 20,00

	Angle	Power
Source 02	0	1
Source 03	30	1
Source 04	40	1
Source 05	45	1

Array Settings

Number of elements: 10

σ^2 of sensor amplitude perturbations: 0,03

σ^2 of sensor phase perturbations: 0,03

Algorithms

- ☑ Bartlett Beamforming
- ☑ Capon (MVDR) Beamforming
- ☑ MUSIC
- ☑ ROOT MUSIC
- ☑ LS-ESPRIT
- ☑ TLS-ESPRIT

Output Options

- ☑ Display Plots

Plot Types

- ☑ Pseudospectrum Plots
- ☑ Angle Estimates Plots

- ☐ Save Detailed Estimates Information

Path

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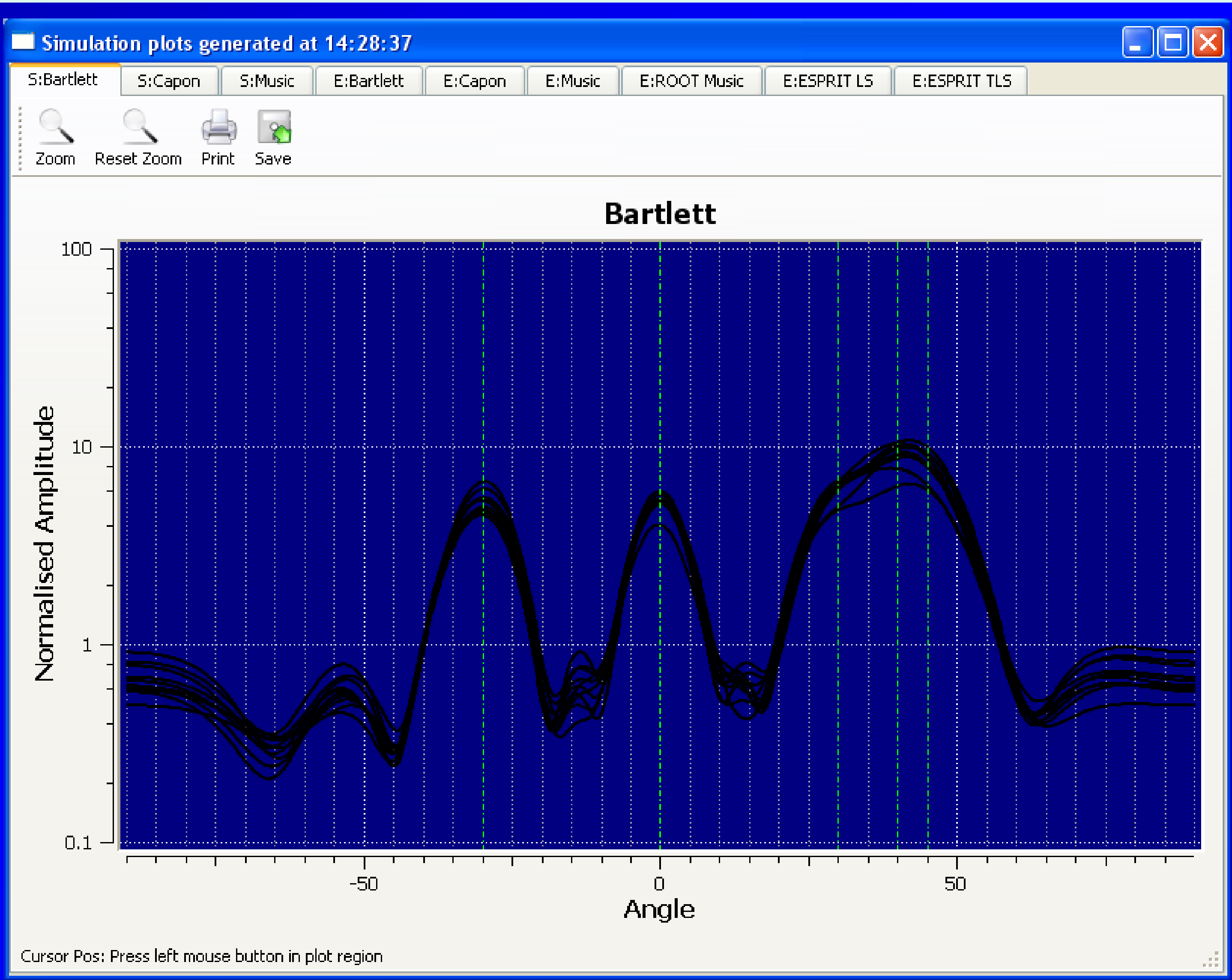
Number of elements – 10; Number of sources – 5; -30; 0; 30; 40; 45. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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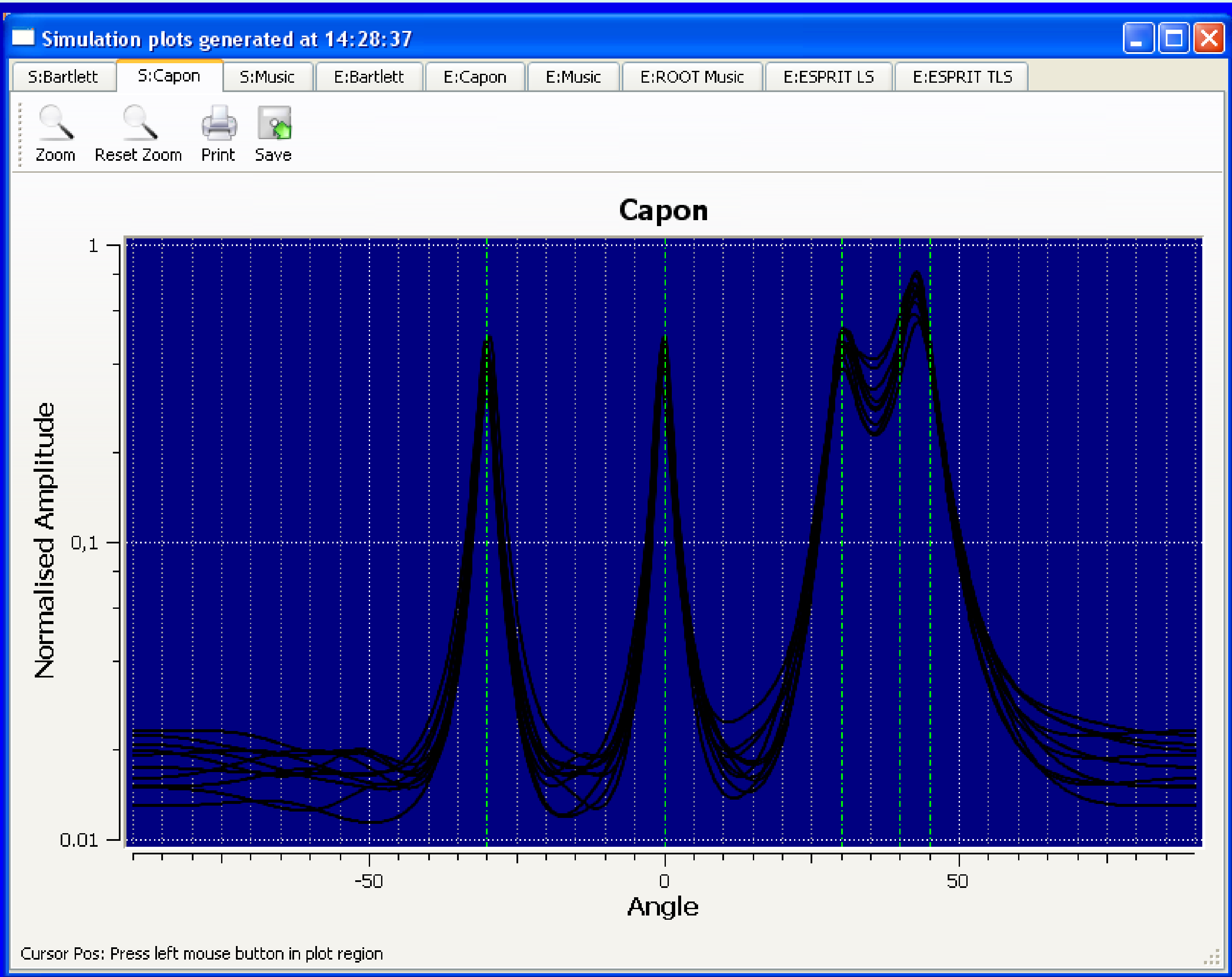
Number of elements – 10; Number of sources – 5; -30; 0; 30; 40; 45. SNR = 20 dB



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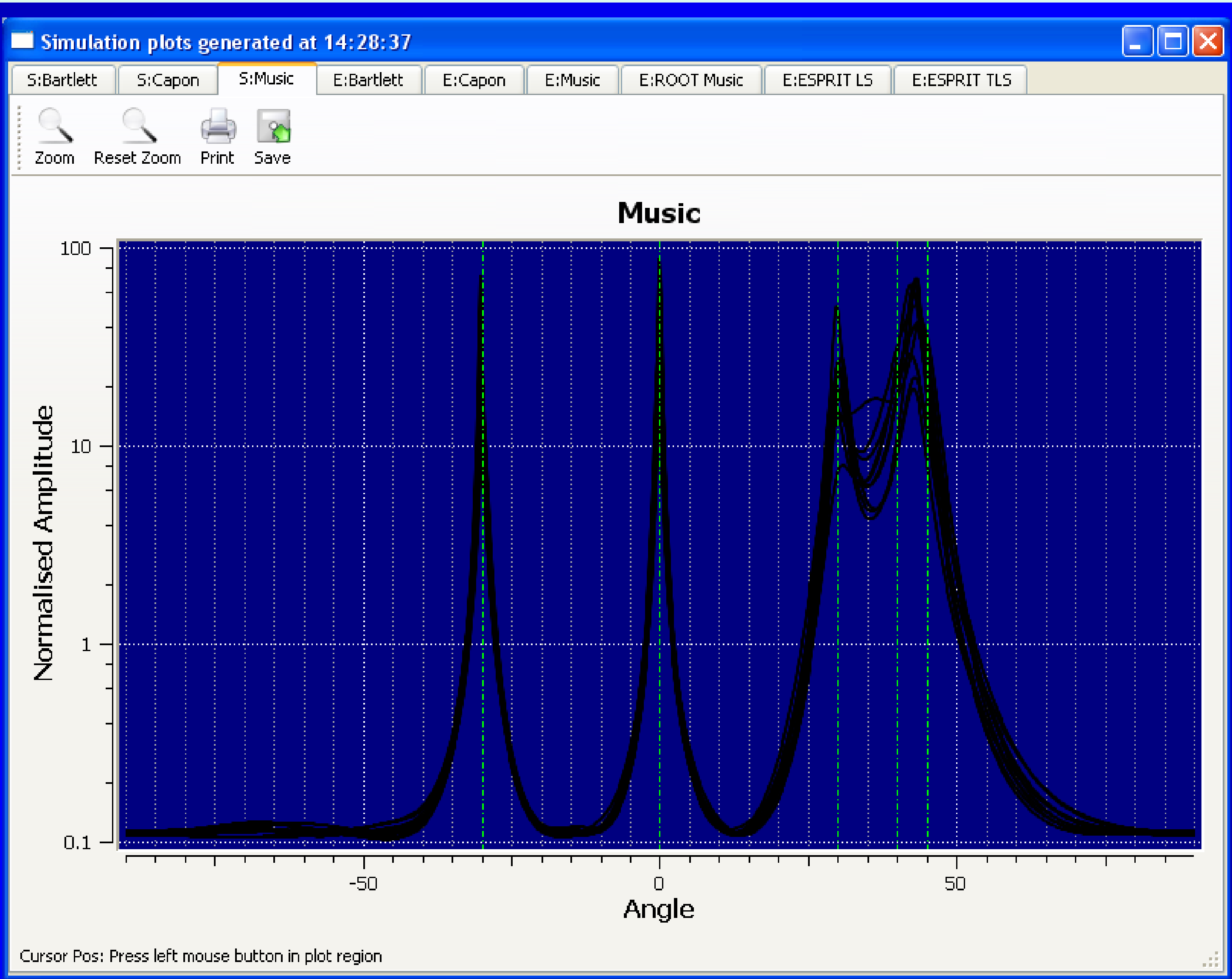
Number of elements – 10; Number of sources – 5; -30; 0; 30; 40; 45. SNR = 20 dB



Cursor Pos: Press left mouse button in plot region

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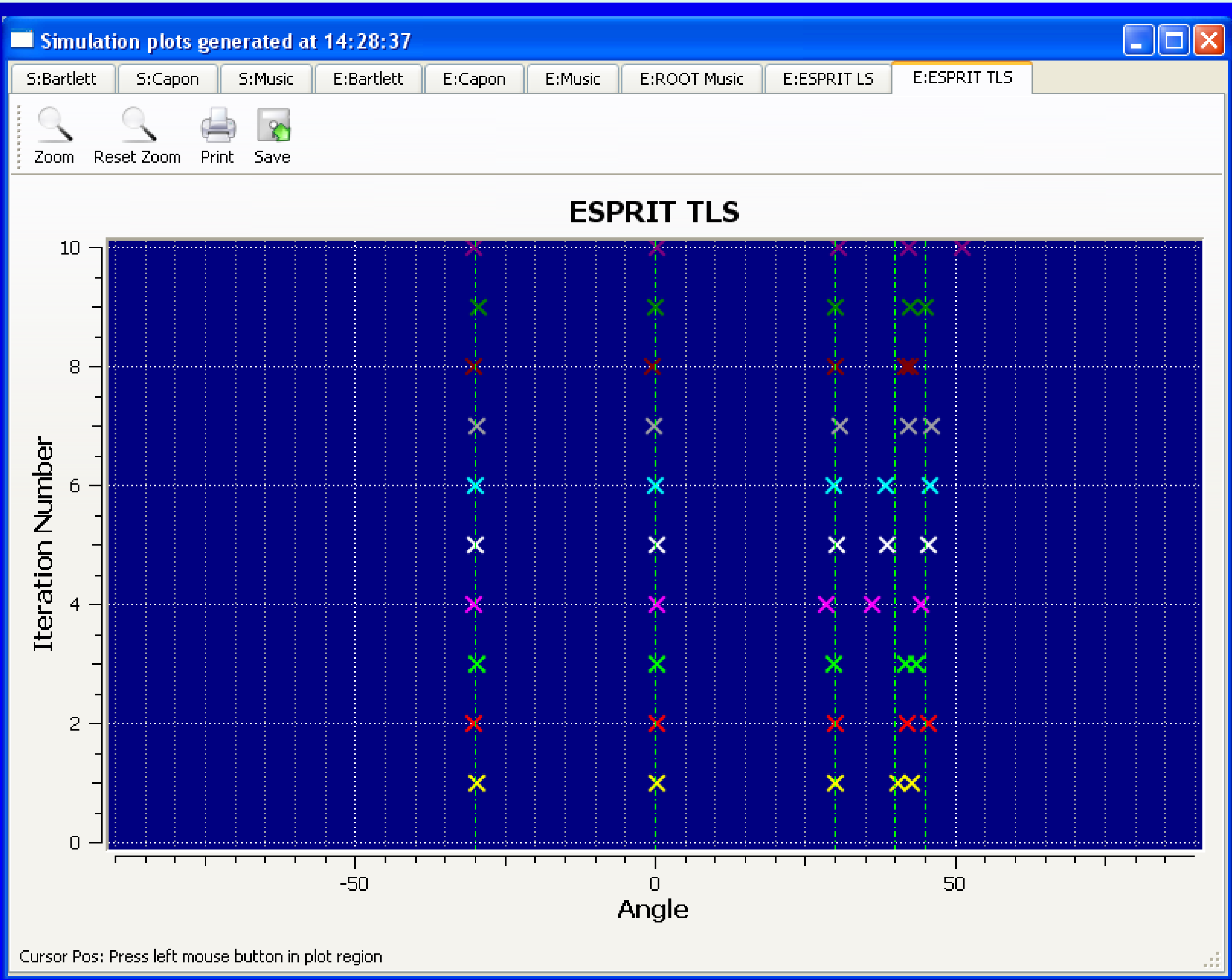
Number of elements – 10; Number of sources – 5; -30; 0; 30; 40; 45. SNR = 20 dB



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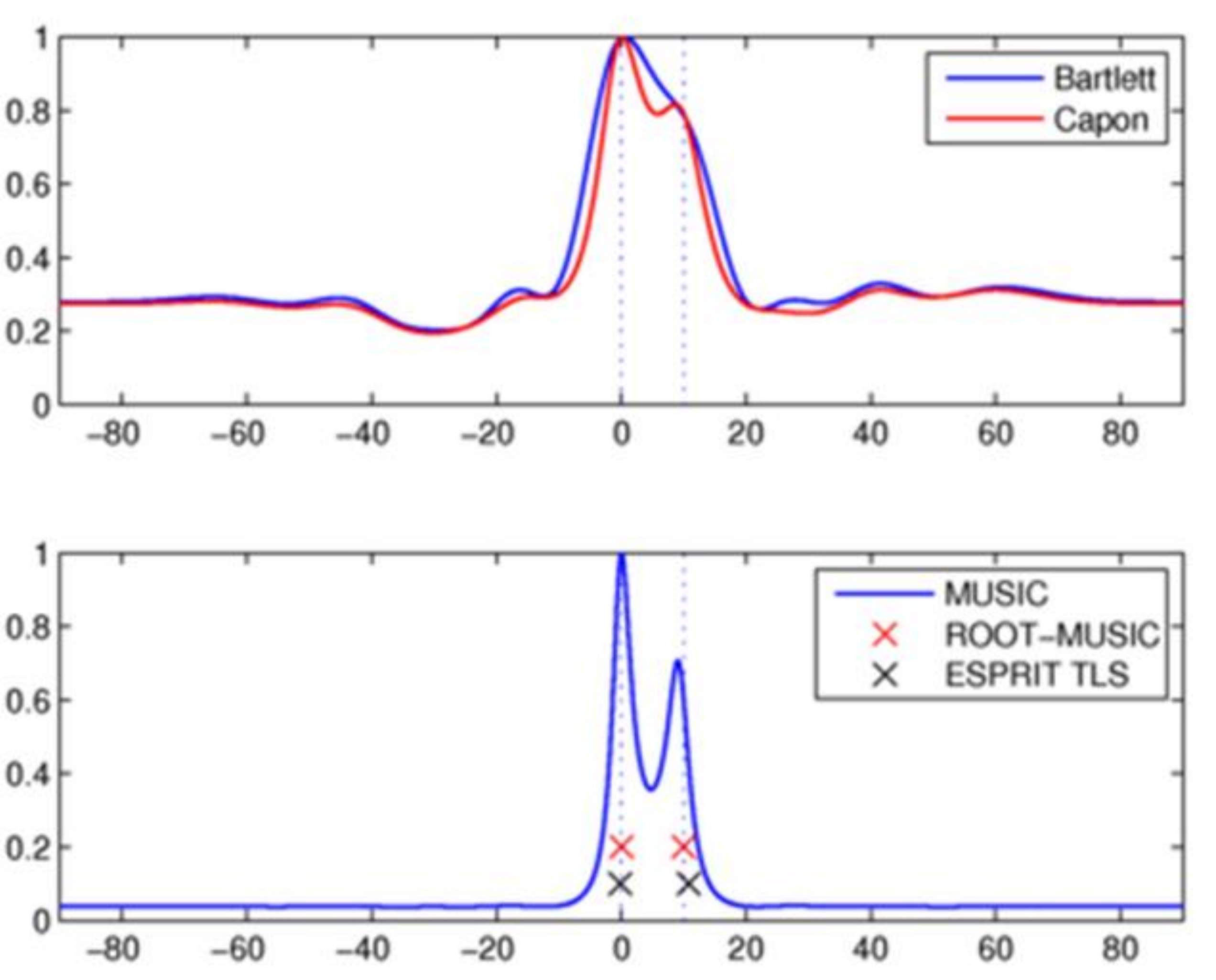
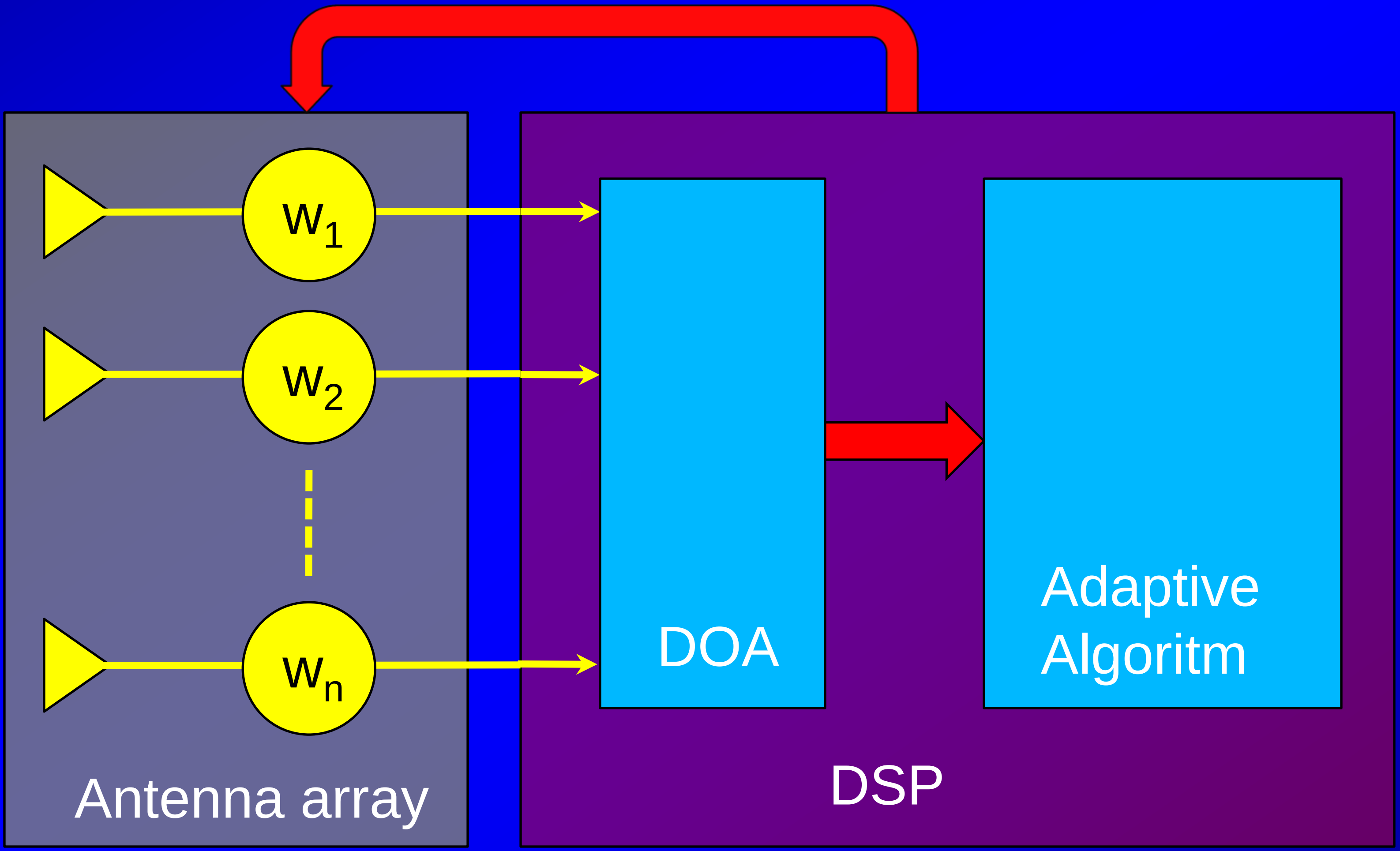
BEHAVIOR OF THE ALGORITHMS FOR NEAR PLACED SOURCES



Smart Antenna



DOA – direction of arrival; DSP – digital signal processor

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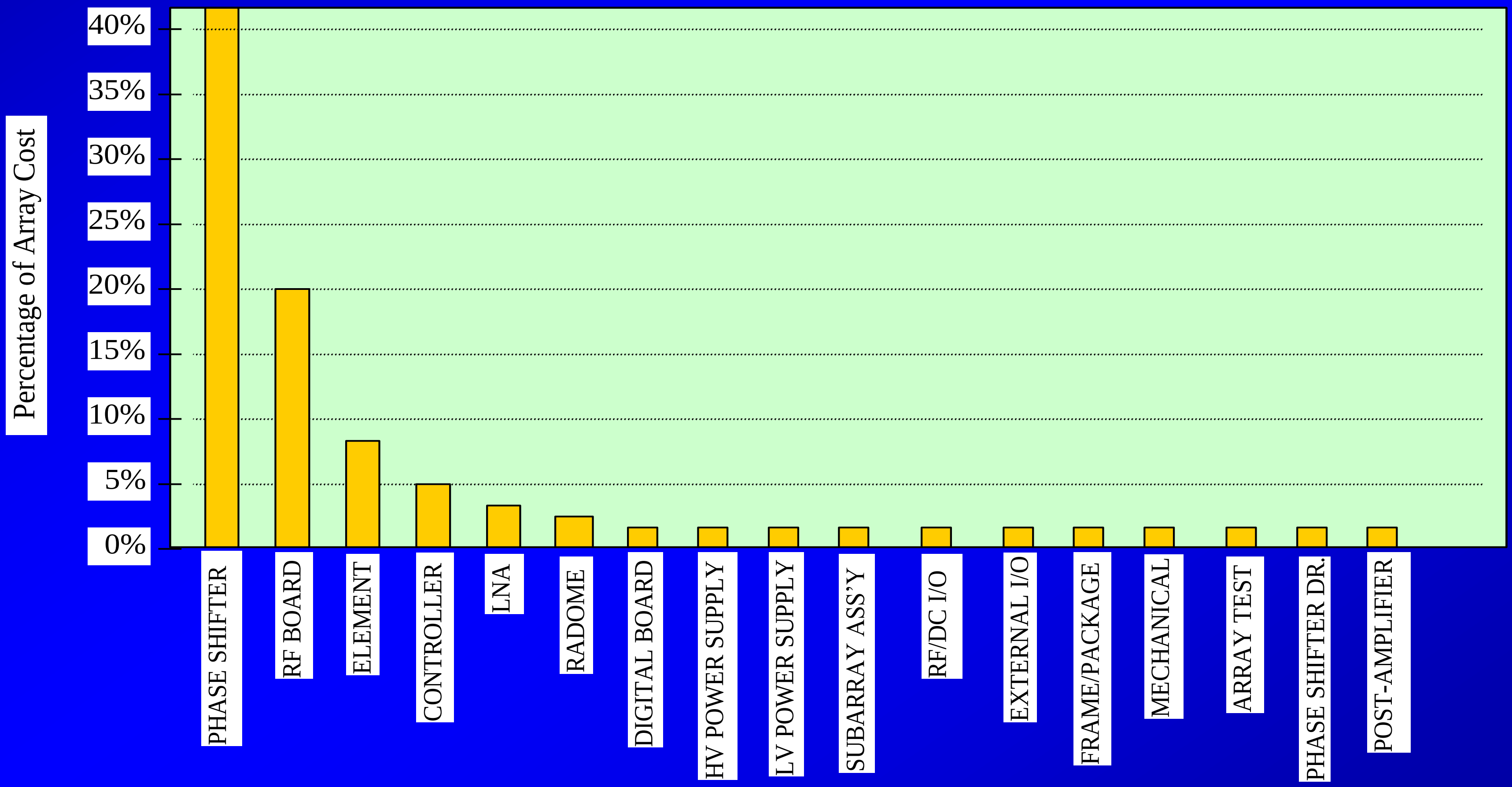
The most prominent obstacle to reduce the cost of phased array is the cost of current phase shifter elements.



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Antenna’s role will radically change in future

- In future smart radios, the antenna will have a crucial importance in signal processing, picking up the wanted RF signal and preventing the unwanted signals from coming in by filtering them in the space, time and frequency domains.

- The antenna will also adapt itself to the changing transmission requirements and signal environments.

- The antenna’s physical structure will less than today limit it’s performance.

- The future antenna will be a reconfigurable aperture antenna that controls different parameters such as operation frequency, bandwidth, impedance match, and beam direction or width.

- However, major technology leaps in eg. material technologies or nonlinear innovation in design methods would be needed to fulfill all the expectations

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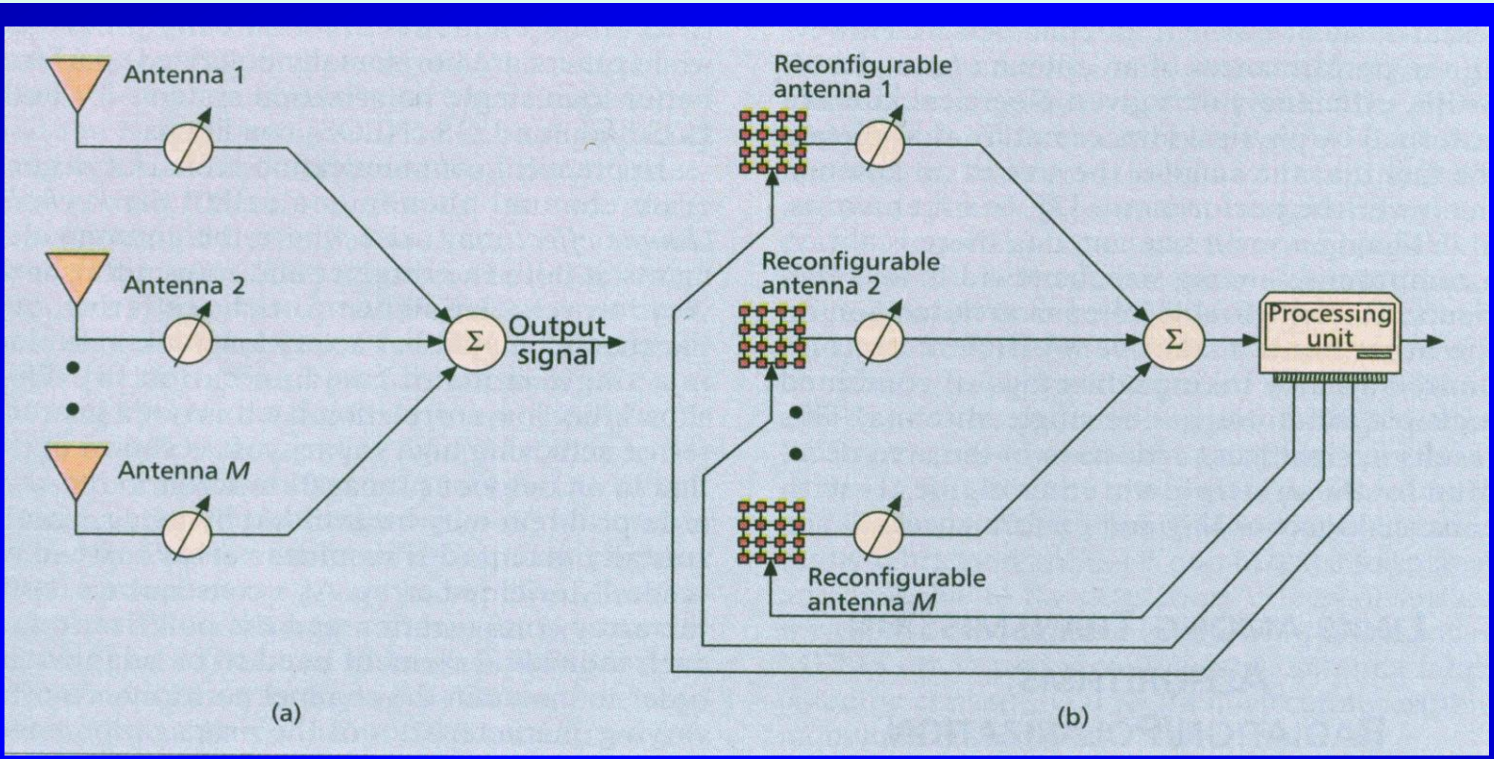
Reconfigurable Antennas CONCEPTS

Reconfigurable Antenna



Conventional antenna array - The antenna elements themselves do not posses any intelligence.

Reconfigurable antenna array – the antenna elements have some intelligence. This intelligence stems from the ability to reconfigure the physical structure of individual elements through which polarization/radiation and frequency properties of the array are changed.

* [1] B. A. Cetiner, H. Jafarkhani, J. –Y. Qian, H. J. Yoo, A. Grau, F. de Flaviis. „ Multifunctional Reconfigurable MEMS Integrated Antennas for Adaptive MIMO Systems”IEEE Communications Magazine, December 2004, Vol. 42, No.12.

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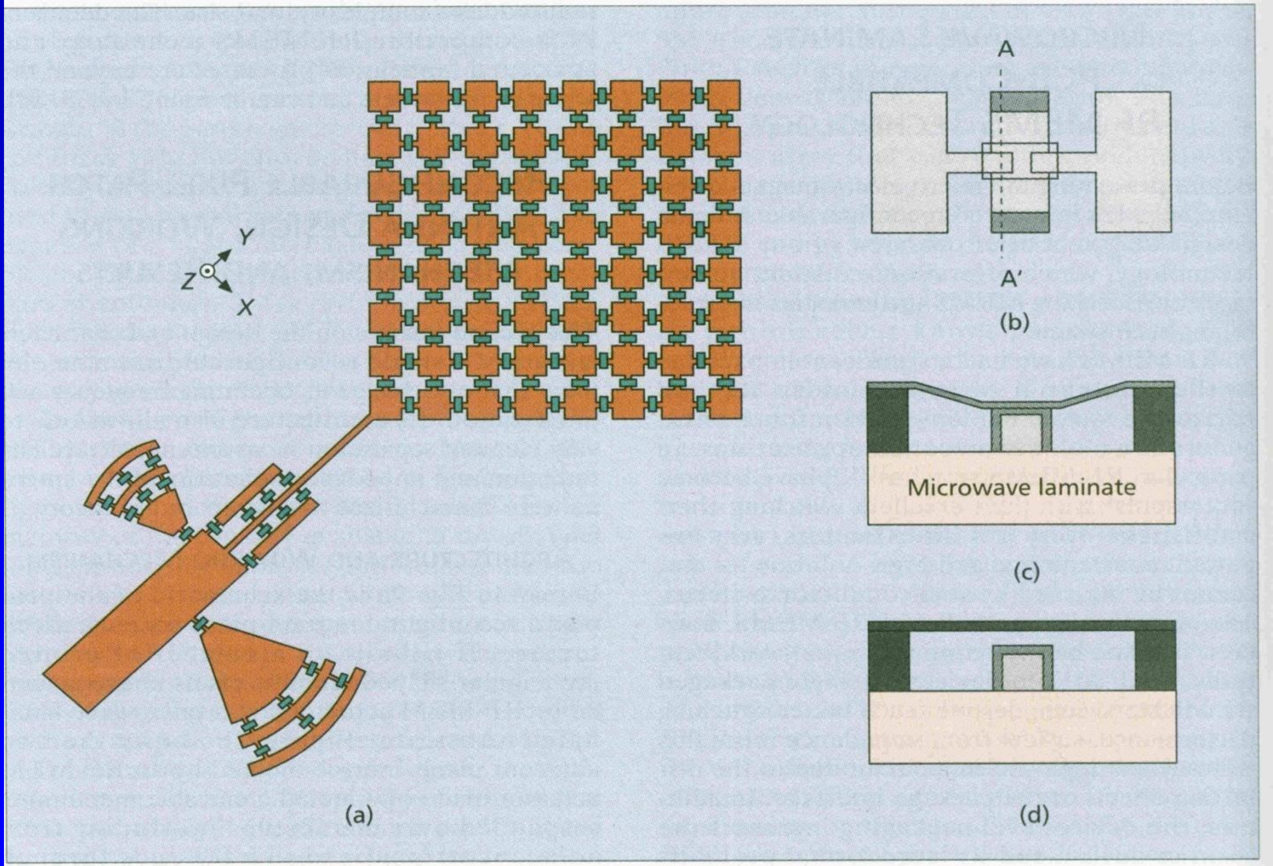
Reconfigurable pixel-patch Antenna



a) schematic of the reconfigurable pixel-patch antenna architecture

b) top view of the MEMS switch;

c) side view

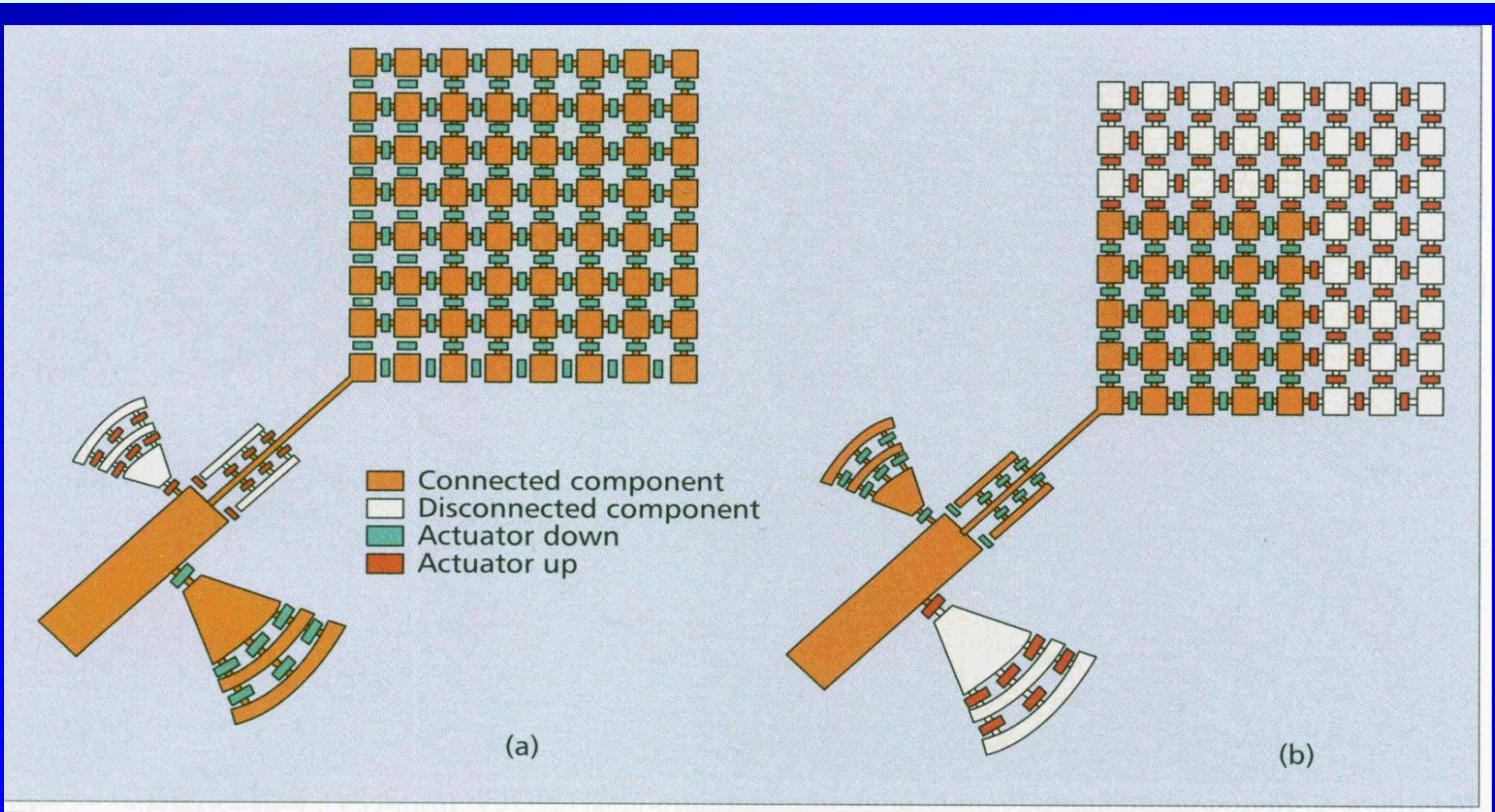
(down position);

d) side view

(up position)

Concept of the reconfigurable aperture derived from fragmented aperture design where the configuration of the fragmented aperture may be switched by the user to obtain different functionalities by opening or closing different connections between these patches.

Reconfigurable 64 pixel-patch antenna for dual frequency operation



Frequency reconfigurability is achieved by simply changing the size of the antenna.

a) The lower f1=4.1 GHz, (all 64 pixels are connected)

b) the upper f2=6.4 GHz (only 25 pixels are connected)

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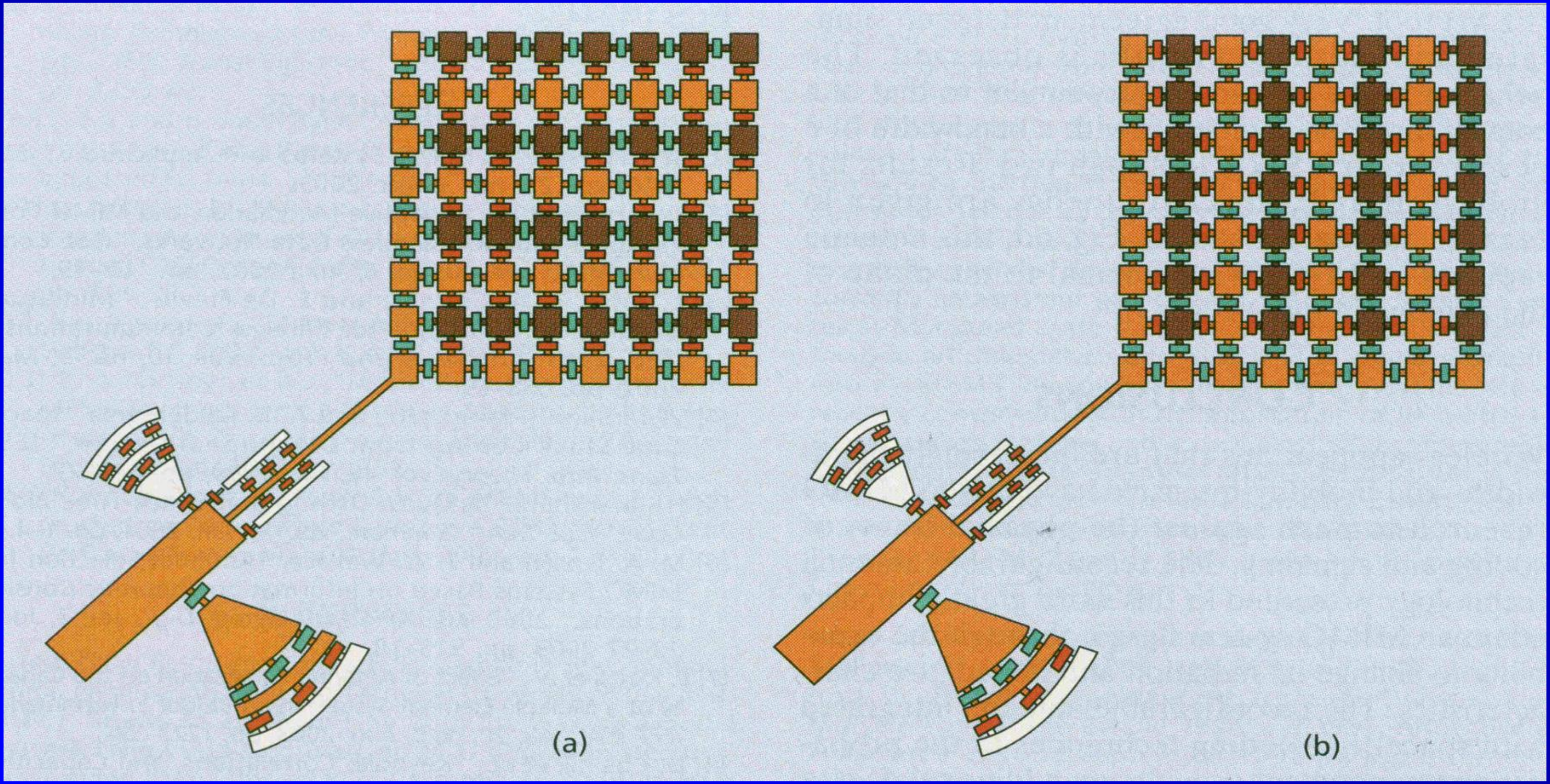
Reconfigurable 64 pixel-patch antenna for linear polarization at 4.1 GHz



Linear X or linear Y polarization are obtained by connecting the pixels either in only the X or only the Y direction, respectively

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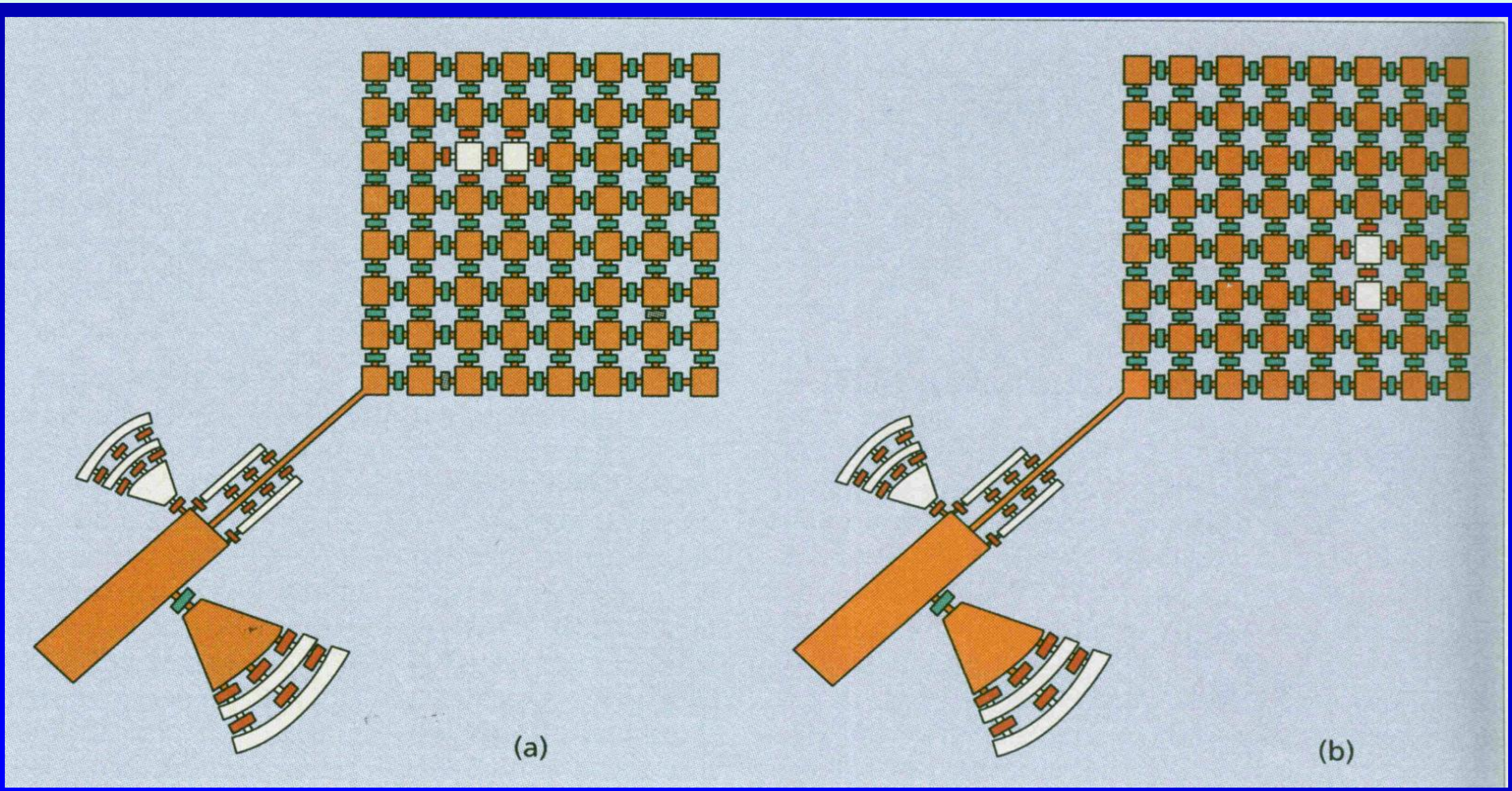
Reconfigurable 64 pixel-patch antenna for circular polarization at 4.1 GHz



a) Right-hand circular polarization, b) Left-hand circular polarization

To obtain circular polarizations is used the antenna geometries with internal slots having proper dimensions and locations for a given operating frequency. Deactivation of the switches introduces these internal slots into pixel-patch antenna geometry

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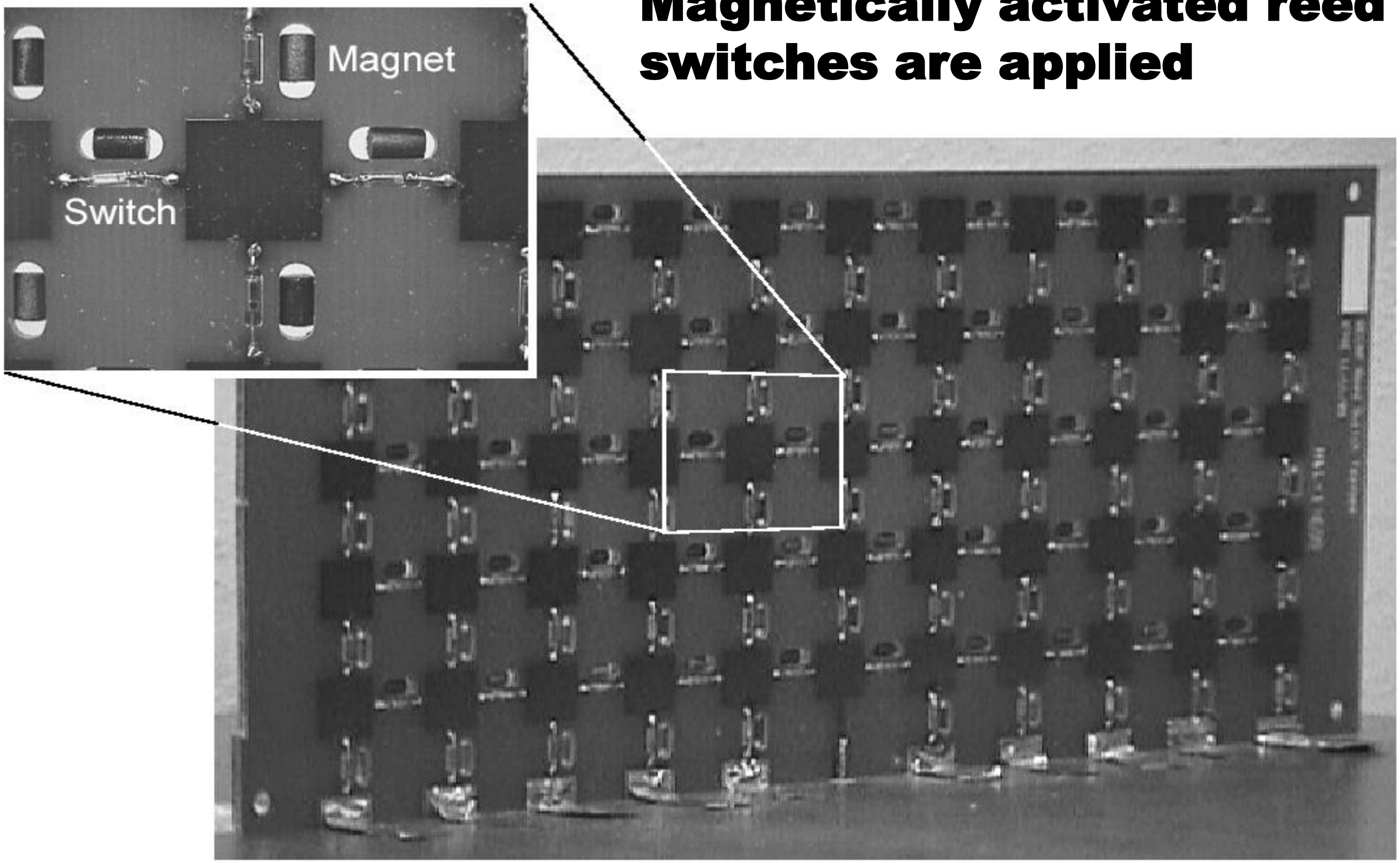
An example of realized Reconfigurable pixel-patch antenna

Magnetically activated reed switches are applied



[4] L. N. Pringle, P. H. Harms, S. P. Blalock, and all. *A Reconfigurable Aperture Antenna Based on Switched Links Between Electrically Small Metallic Patches*. IEEE Trans. on Antenna and Propagation. AP-52, No. 6, June 2004, pp. 1434 – 1445.

Several important characteristics that must be evaluated for all RF switch applications and particularly reconfigurable antenna designs.

The selection of switch type required by the application depends fundamentally on the:

- **Switching speed**
- **Switched signal power level**
- **Impedance characteristics (switch resistance, capacitance and inductance along the RF signal path)**
- **Switch biasing and activations conditions**
- **Package and form factor**
- **Switch cost**

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Comparison of performance of FET, PIN and MEMS switches

Parameter	RFMEMS	PIN	FET
Voltage [V]	20 – 100	3 – 5	3 – 5
Current [A]	0	3 – 20	0
Power Consumption [mW]	0.05 – 0.1	5 – 100	0.05 – 0.1
Switching Time	1 – 200µs	1 – 100ns	1 – 100ns
Cup (Series) [pf]	1 – 6	40 – 80	70 – 140
Rs(Series)[Ω]	0.5 – 2	2 – 4	4 – 6
Capacitance Ratio	40 – 500	10	-
Cutoff Freq. [THz]	20 – 80	1 – 4	0.5 – 2
Isolation (1 - 10 GHz)	Very high	High	Medium
Isolation (10 - 40 GHz)	Very high	Medium	Low
Isolation (60 - 100 GHz)	High	Medium	-
Loss (1 - 100 GHz) [dB]	0.05 – 0.2	0.3 – 1.2	0.4 – 2.5
Power Handling [W]	< 0.5	<10	<10

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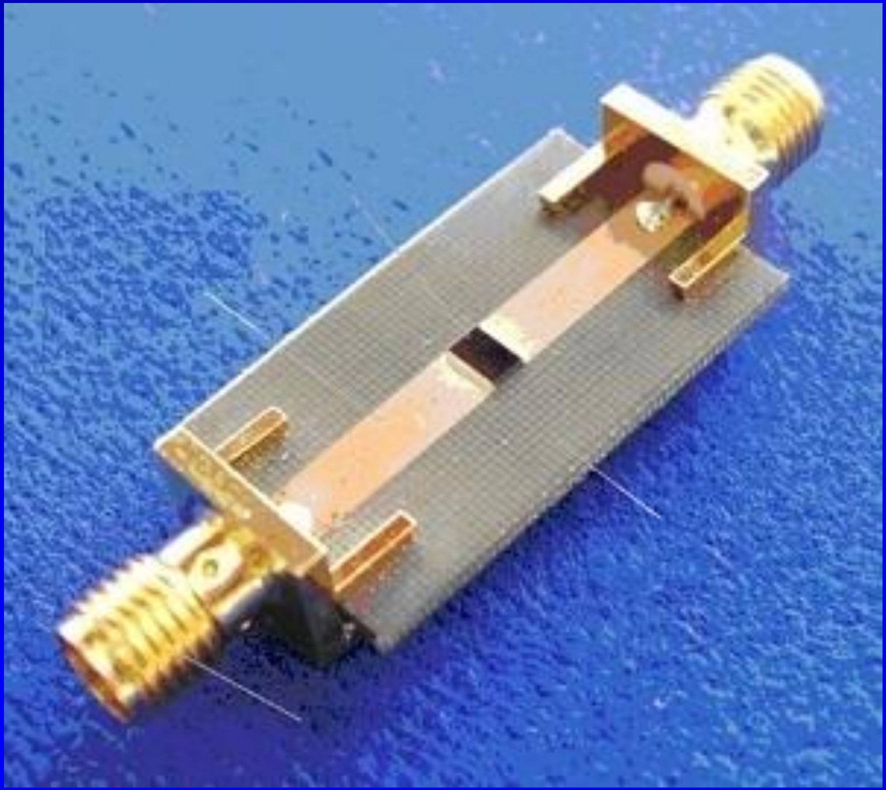
Optically Activated MicroSwitch



- ***Fast Switching***. Can be a good candidate for applications required switching speed as fast as 10.5 μs.

- ***Low EMC Issues***. Light signal used to operate the microswitch does not interfere with EM waves.

- ***High Isolation Characteristics***. Between 1 – 3 GHz frequency range, the switch gives isolation as high as 23dB.

The Si microswitch is diced from wafer of high resistivity (r) silicon (r > 6000 W×cm).

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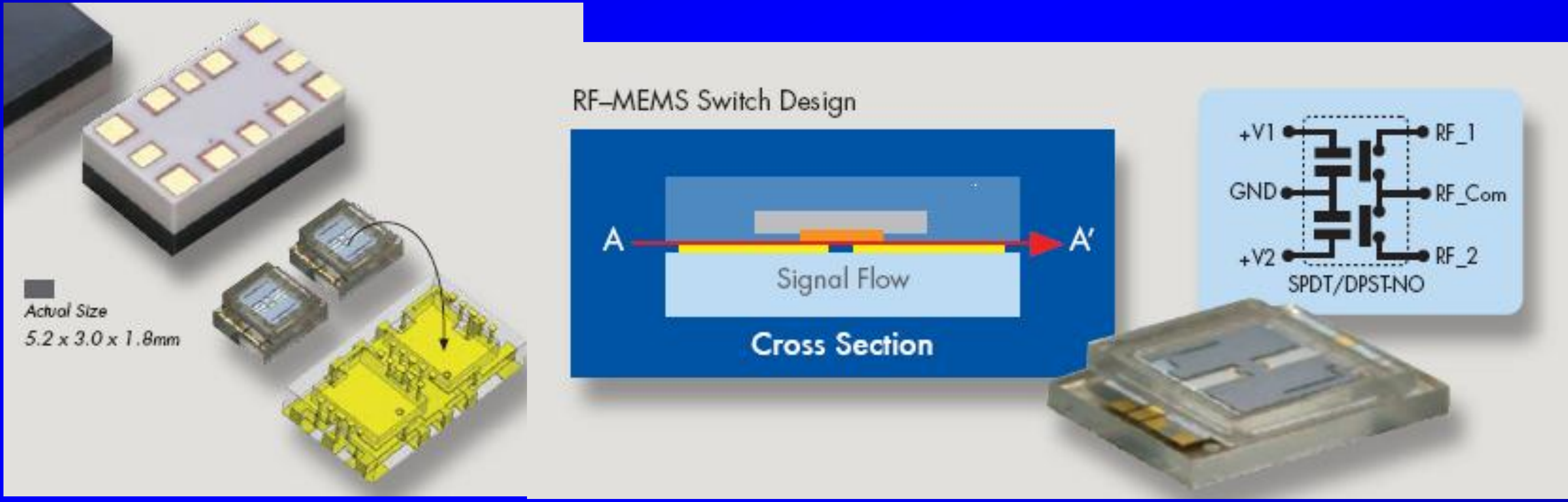
RF MEMS switch for microwave applications

OMRON
ELECTRONIC COMPONENTS LLC
55 Commerce Drive, Schaumburg, IL 60173 U.S.A.



Omron has developed an RF MEMS switch that can handle +36dBm power with 1 dB maximum insertion loss and 30 dB isolation. The rated bandwidth is 8 GHz with typical performance of 10 GHz

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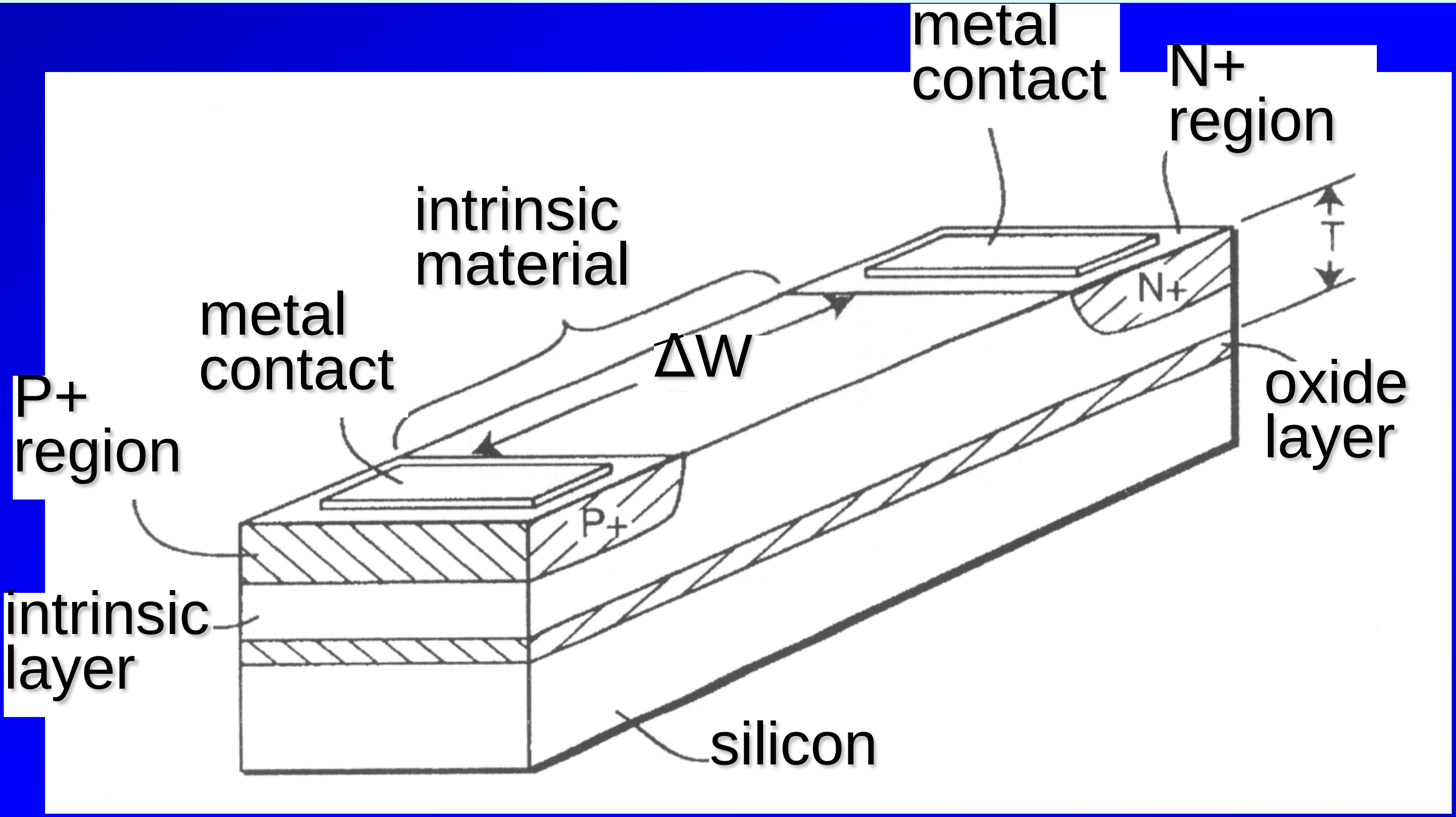
Basic element for semiconductor antennas



The SPIN (Surface PIN Device, US Patent 6617670 B2, Sep. 9, 2003. Taylor et al..) diode, when it is activated (in the “on” state), confines carrier injection to such a small volume near the surface of the device that the device is sufficiently conductive to simulate a planar conductor

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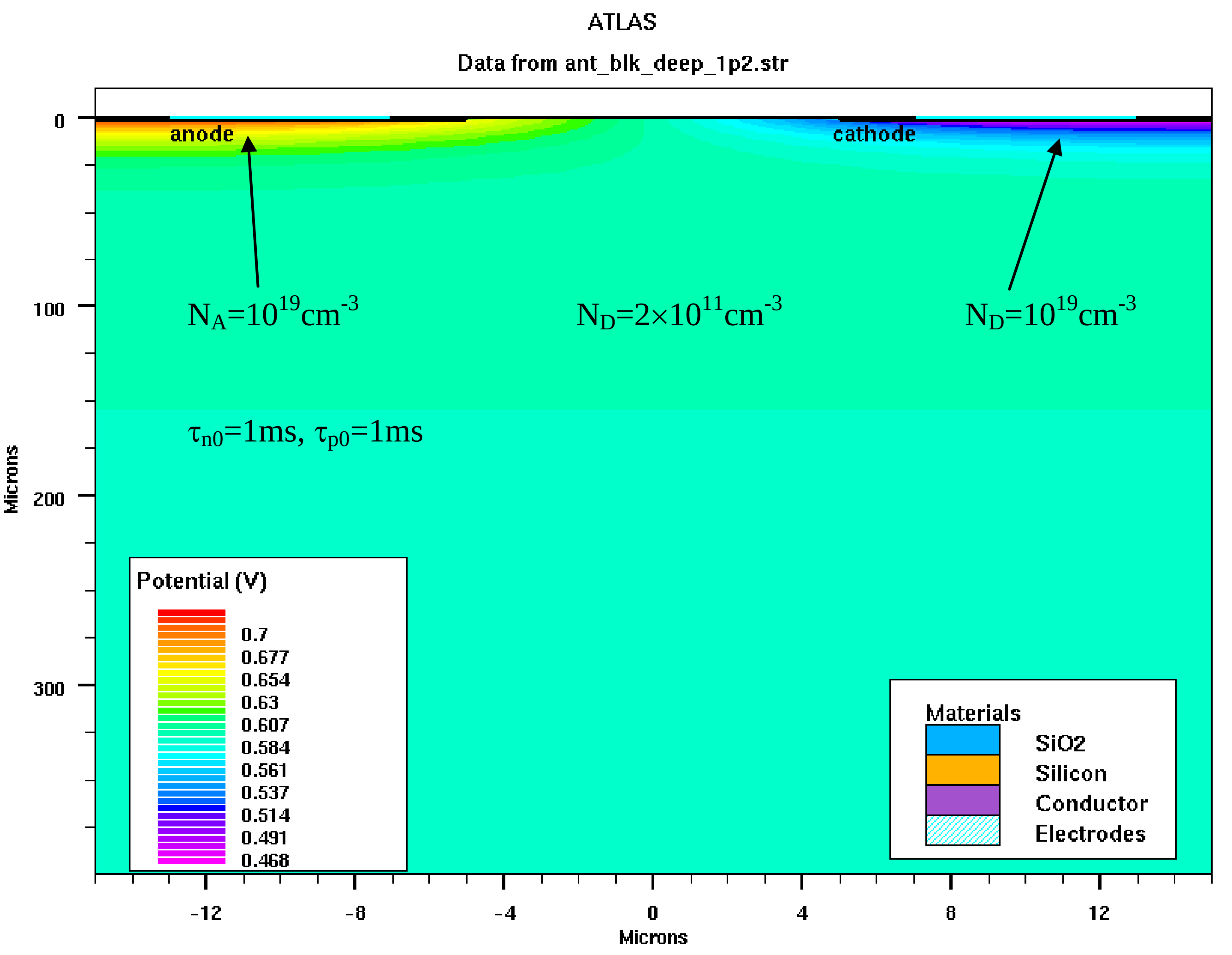
Potential distribution for V_F=1.2V (bulk silicon)



$N_A=10^{19}cm^{-3}$

$N_D=2\times10^{11}cm^{-3}$

$N_D=10^{19}cm^{-3}$

τ_{n0}=1ms, τ_{p0}=1ms

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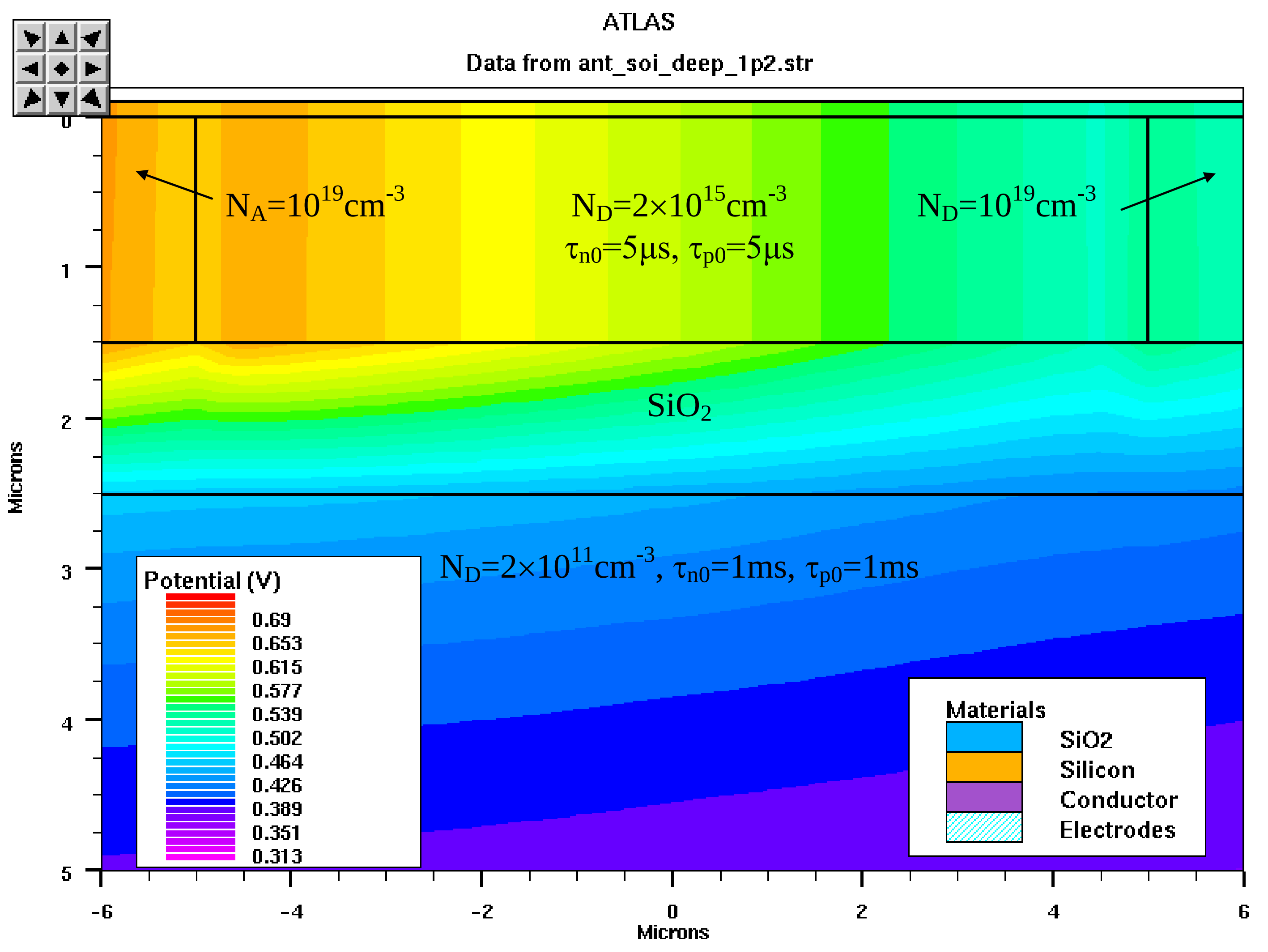
Potential distribution for V_F=1.2V (SOI)



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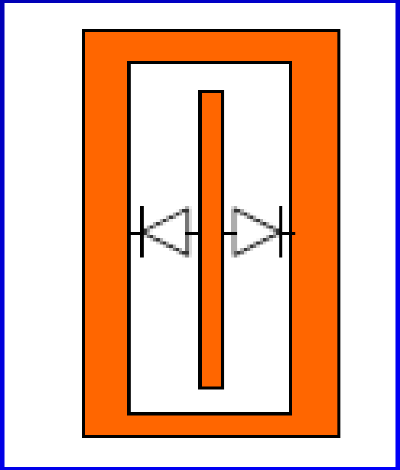
Element of the reconfigurable aperture

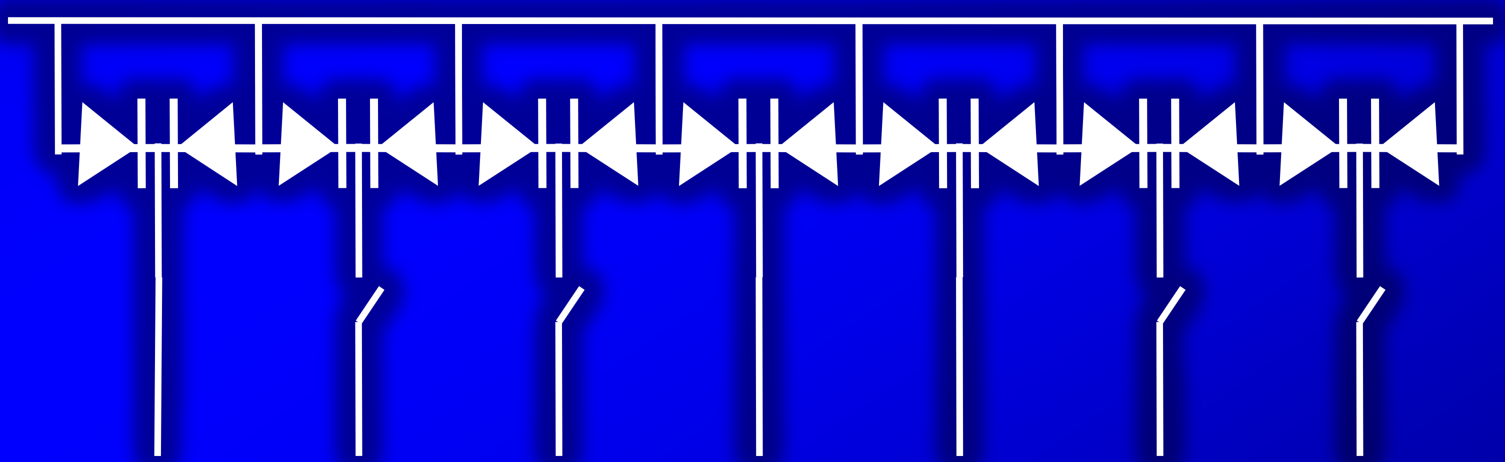


Every reconfigurable element is formed by the SPIN diodes.

The SPIN diodes can be activated independently by means on external DC bias.

It allows to create two states:

1. opened slots – state “off”, SPIN diode is switch off;
2. closed slots – state “on”; SPIN diode is activated.



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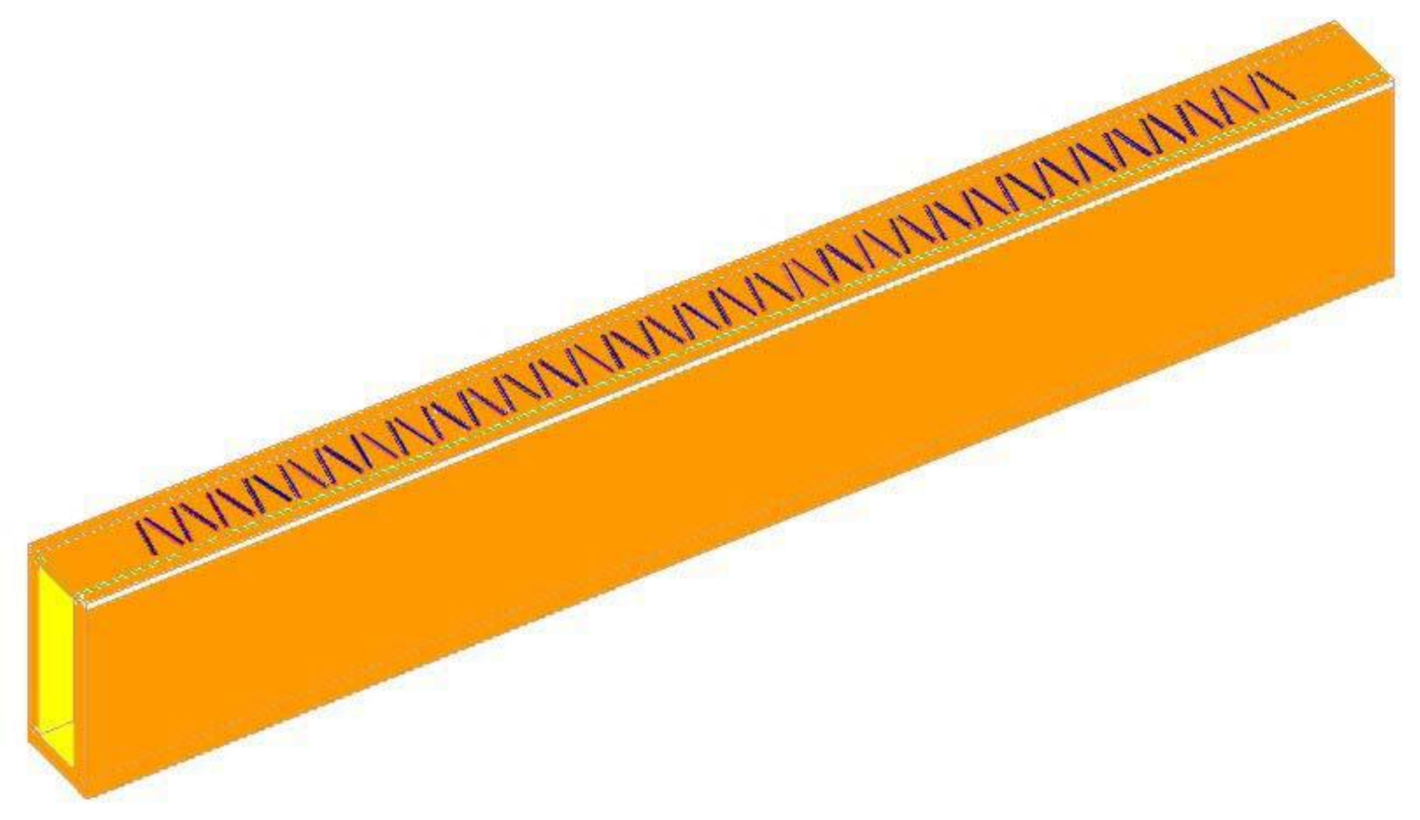
New concept of a reconfigurable antenna



Antenna is based on a waveguide slots array exploiting the reconfigurable aperture instead of the narrow wall of the rectangular waveguide. This aperture has consisted of a lot of pair of the inclined slots, each of which is made as a surface PIN diode on semiconductor layer.

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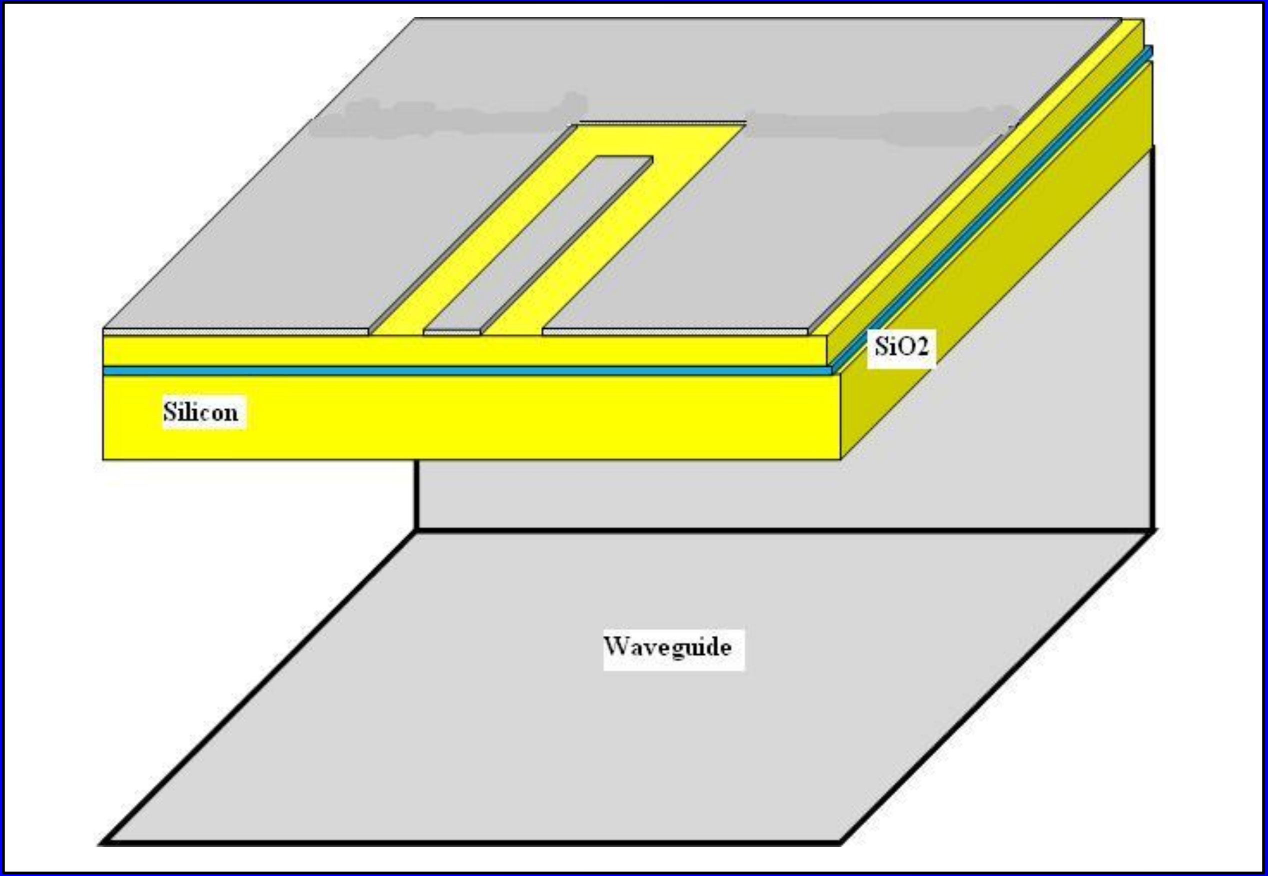
Basic reconfigurable element for presented slot array



The cross section of the reconfigurable radiating slots illustrating the bonded wafer (SOI) structure and SPIN diods placed on the silicon substrate

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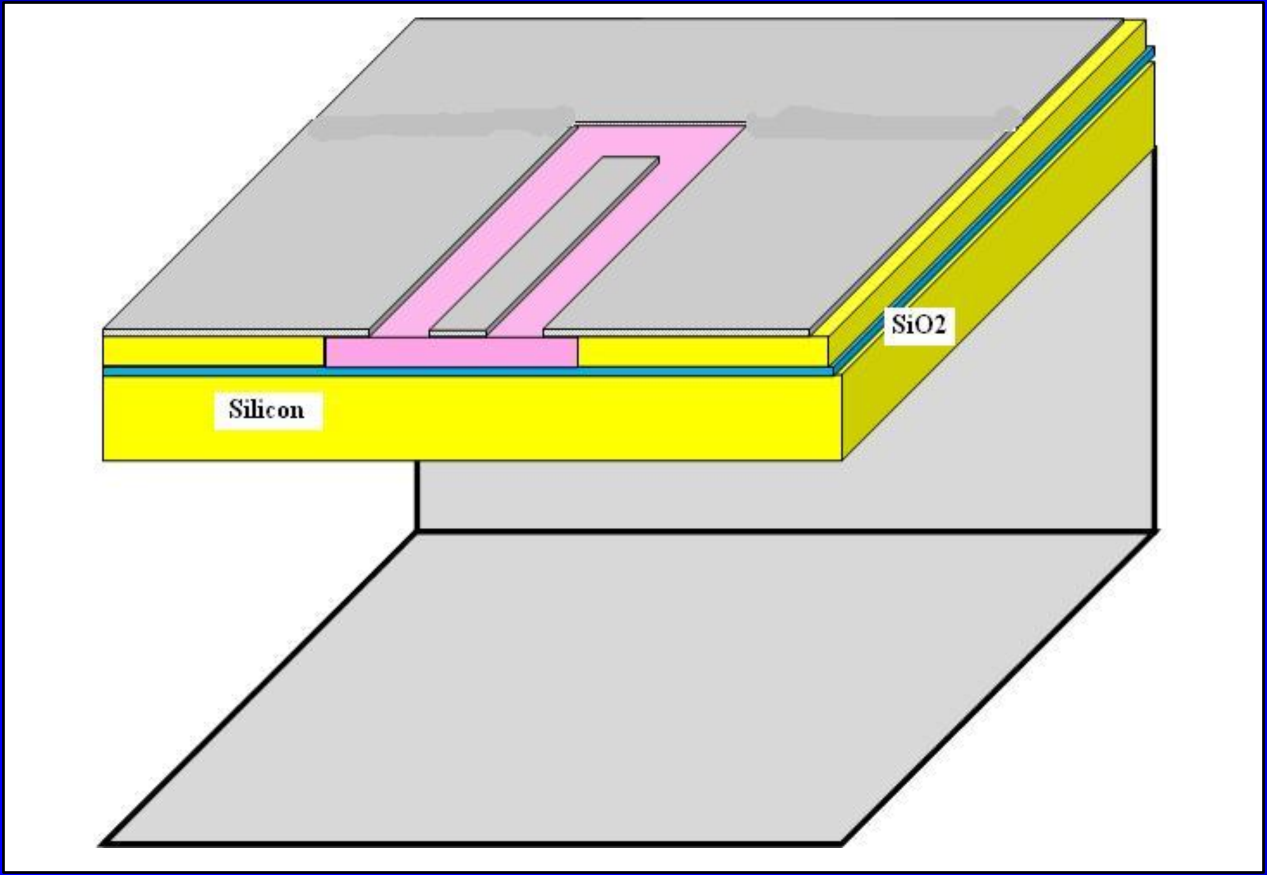
Basic reconfigurable element for presented slot array



When the SPIN diode is activated (in the “on” state), it confines carrier injection to such a small volume near the surface of the device that the device is sufficiently conductive to simulate a planar conductor

Potential distribution at anode bias voltage = 2.5V (SOI wafer)

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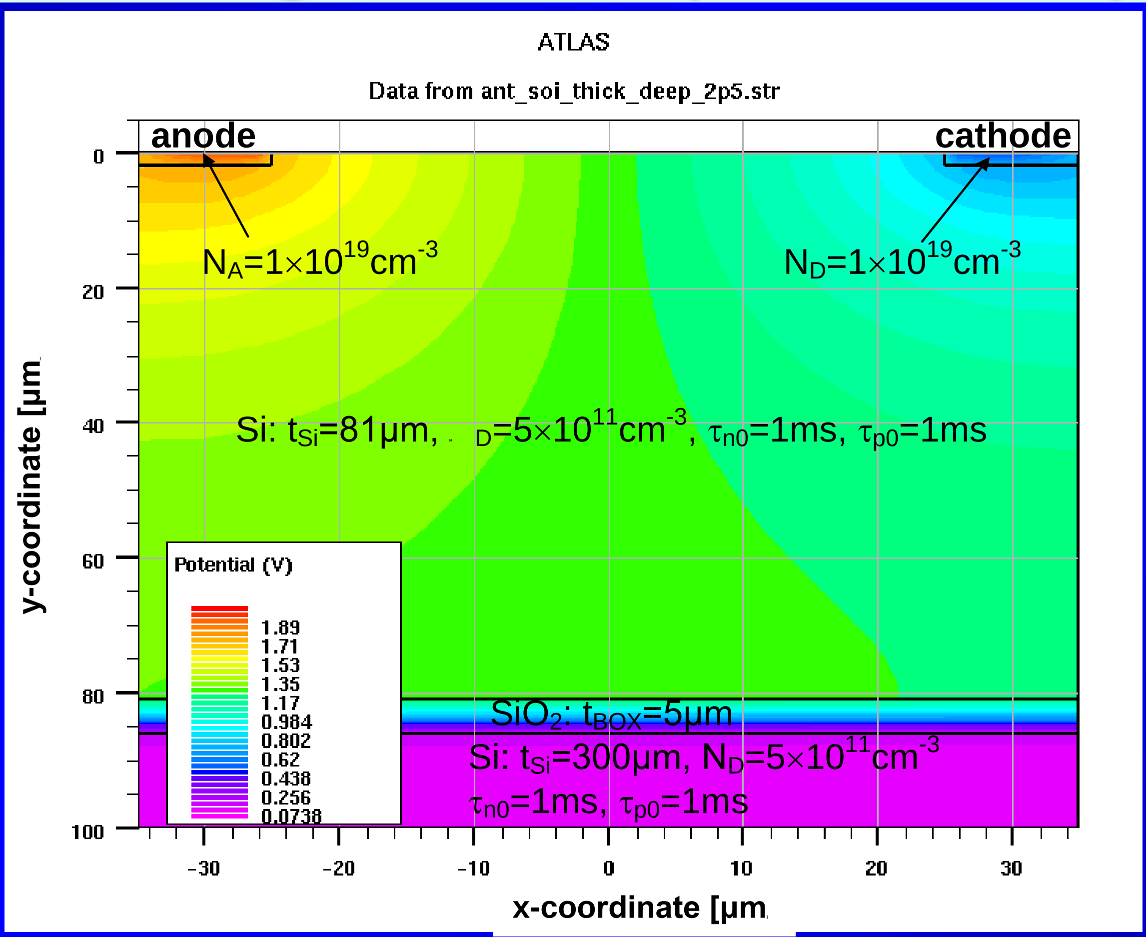

It easy to note that if one biases a SPIN diode strongly in the forward direction it is possible to create well conducting plasma carriers and to shorten the slot.

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Extension of the functionalities of the reconfigurable waveguide slot antenna

- Reconfigurable antenna can generate more than one different radiation patterns at the same frequency
- Reconfigurable antenna can operate at different frequencies with supporting radiation in the same or similar direction.

Drawback:

the direction of the beam can be chosen in a discrete way.

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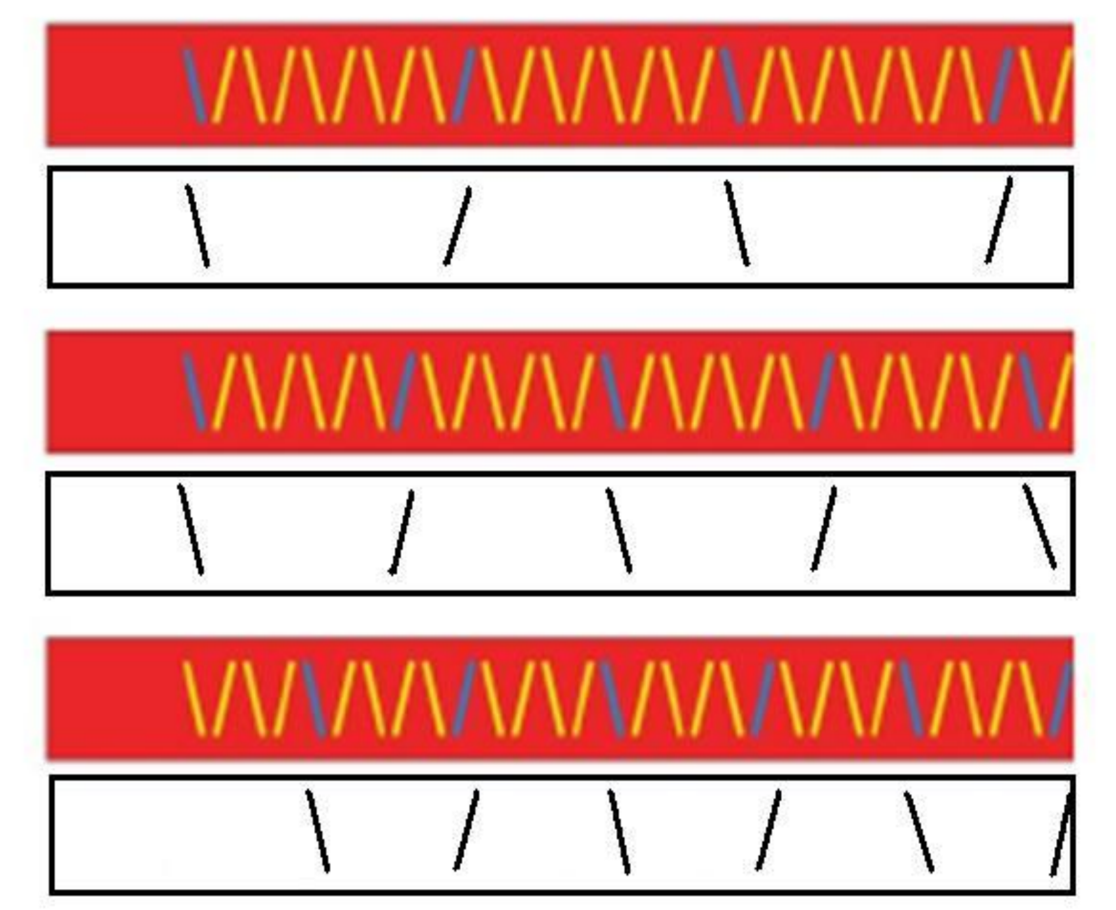
Examples of the three different configurations of the slots structure – in the result – three different antennas by using the same aperture



1-8on-1

First slot - in state “off”, next 8 slots - in state “on” and the tenth slot is working in state “off”

1-6on-1

First slot - in state “off”, next 6 slots - in state “on” and the seventh slot is working in state “off”

1-4on-1

Four slots – in state “on” The fifth slot is radiated, four next slots are again in state “on” and the tenth slot is working in state “off”

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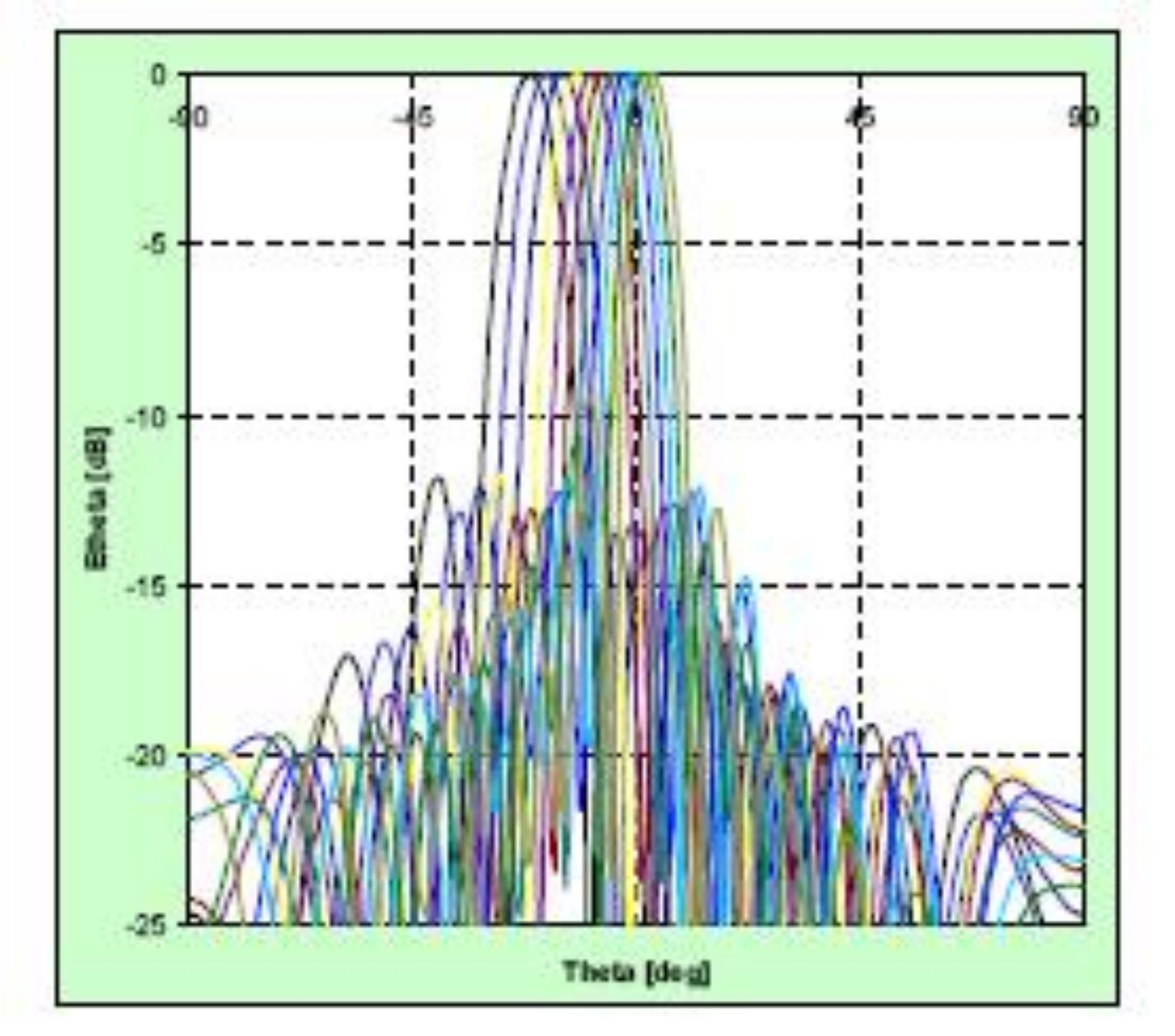
Radiation patter of the 1-4on-1 antenna for frequencies from 26 GHz to 36GHz



Conventional frequency scanning antenna

The direction of main beam can be changed from -21 to 3 degrees by changing the frequency from 26 GHz to 36 GHz

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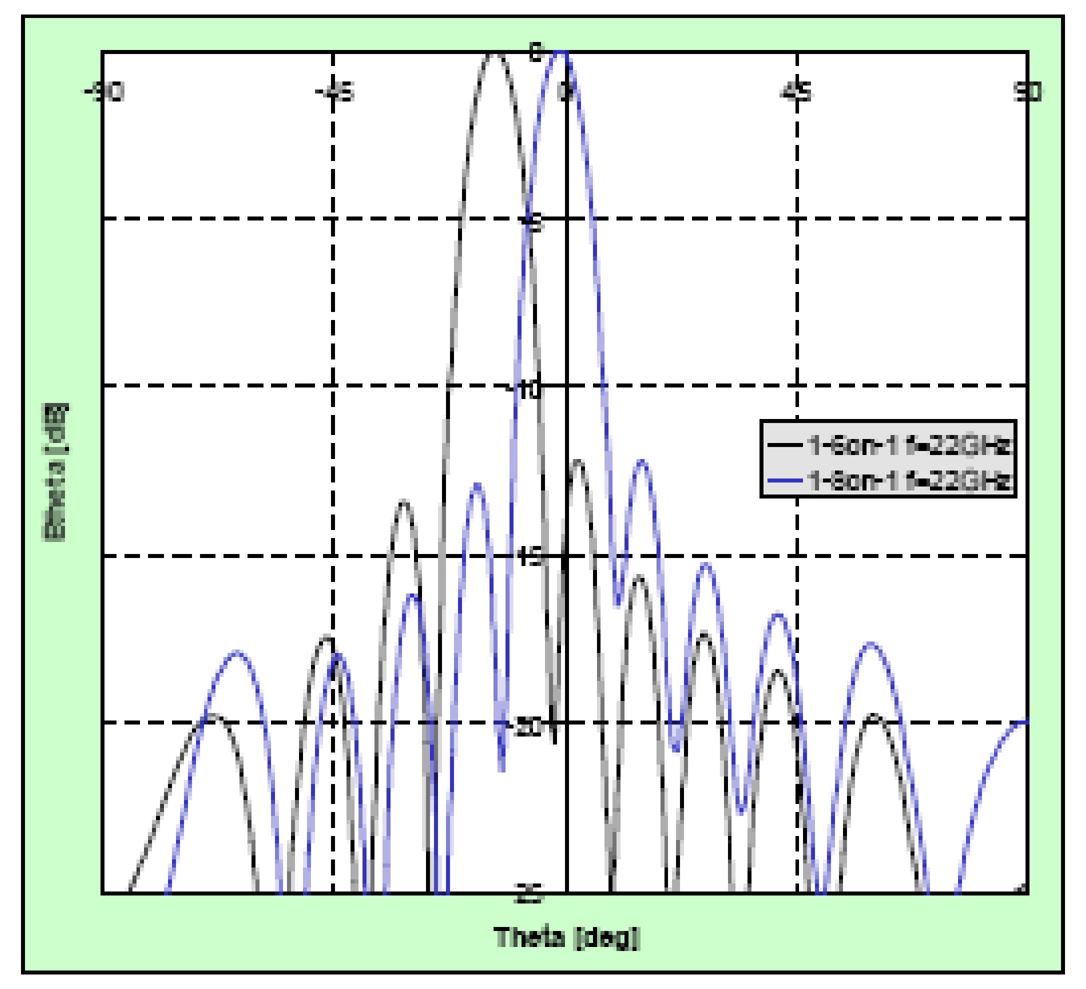
Radiation patter of the 1-8on-1 and 1-6on-1 configuration for frequencies 22GHz



The first additional possibility in comparison with conventional waveguide slot antenna:

Reconfigurable antenna can be used for operating at one frequency, but with generating two or more different radiation patterns at different moments

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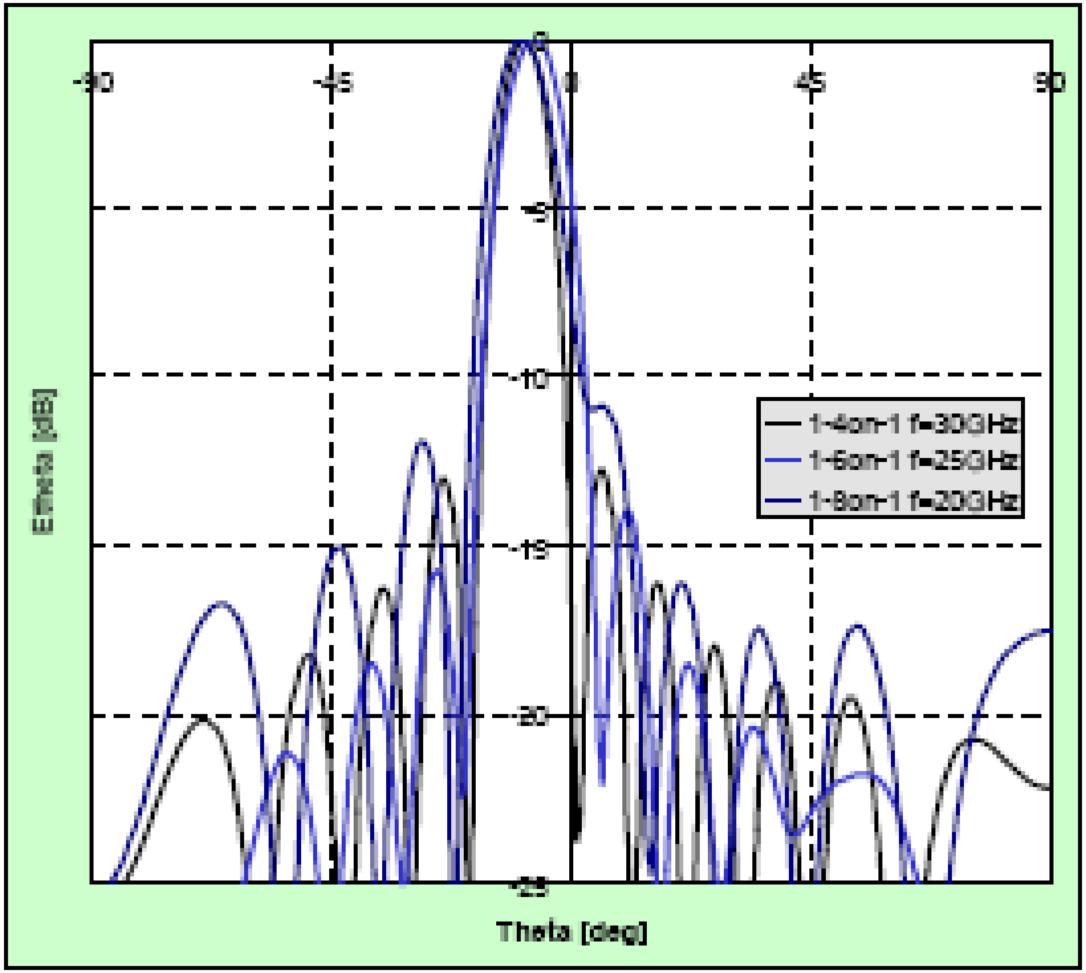
Radiation patter of the: 1-8on-1 configuration for 20GHz, 1-6on-1 configuration for 25GHz and 1-4on-1 configuration for 30GHz



The second extending possibility of the presented reconfigurable antenna:

Reconfigurable antenna can operate at different frequencies with supporting radiation in the same direction

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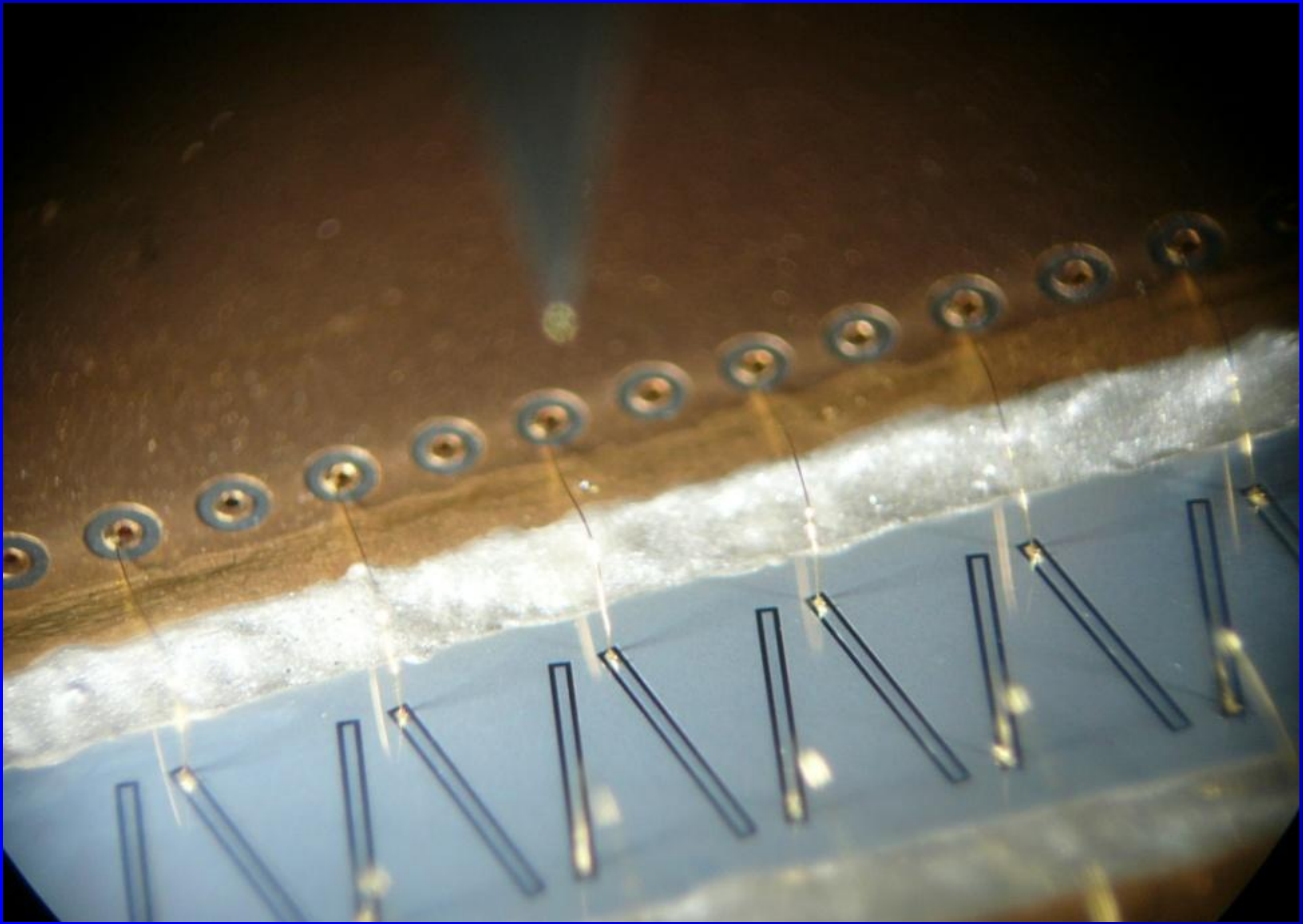
Aperture construction of reconfigurable antenna



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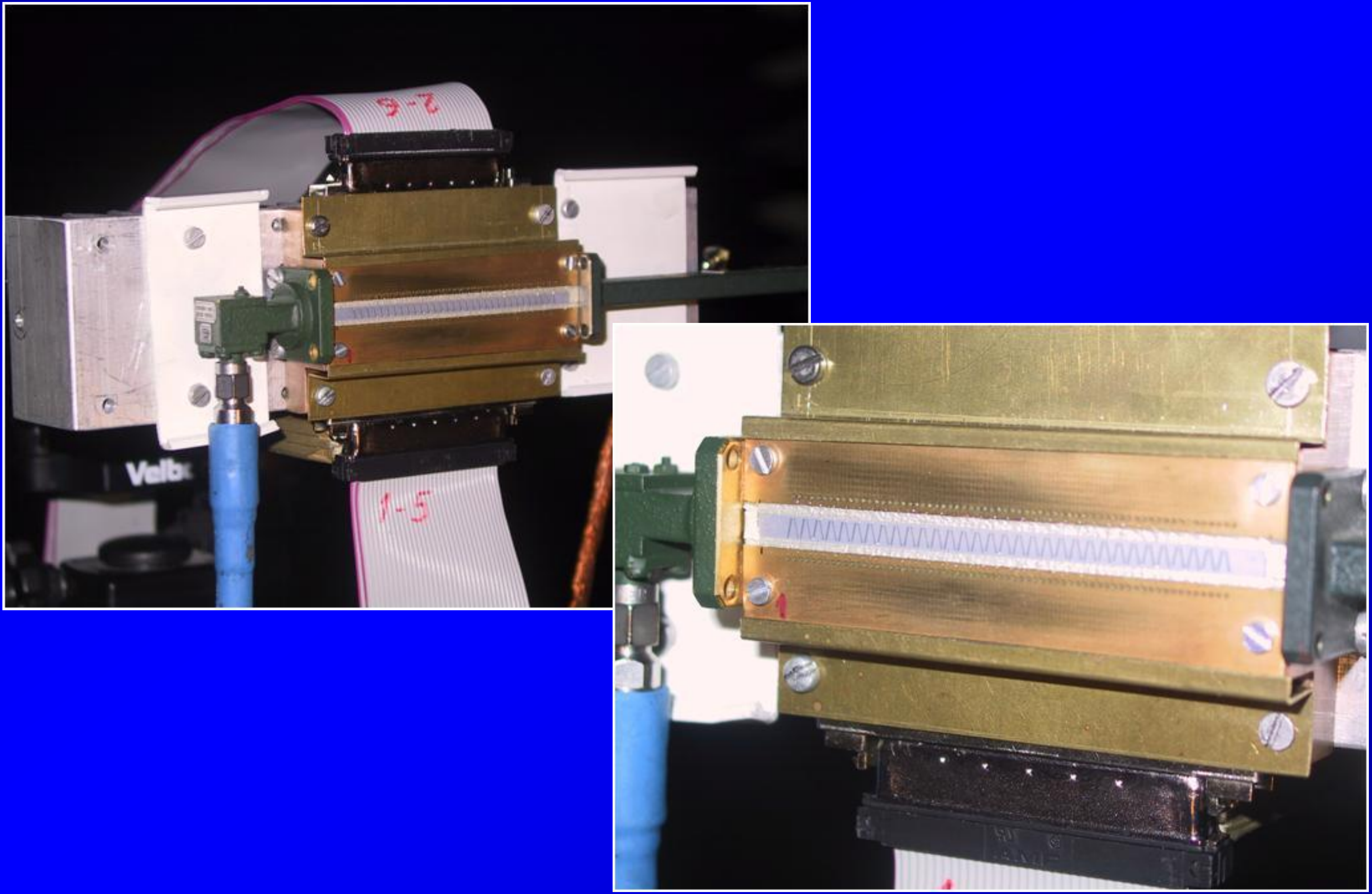
Reconfigurable antenna construction



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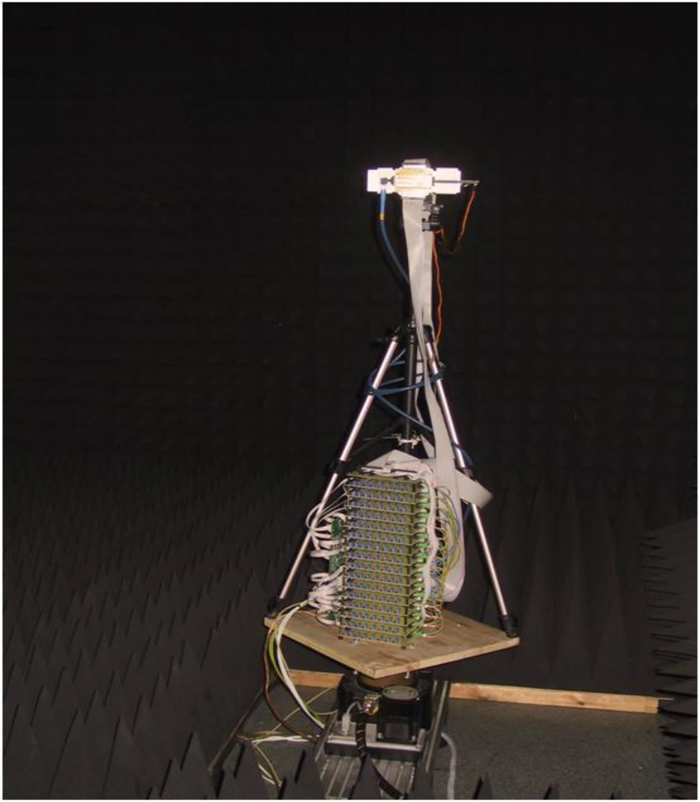
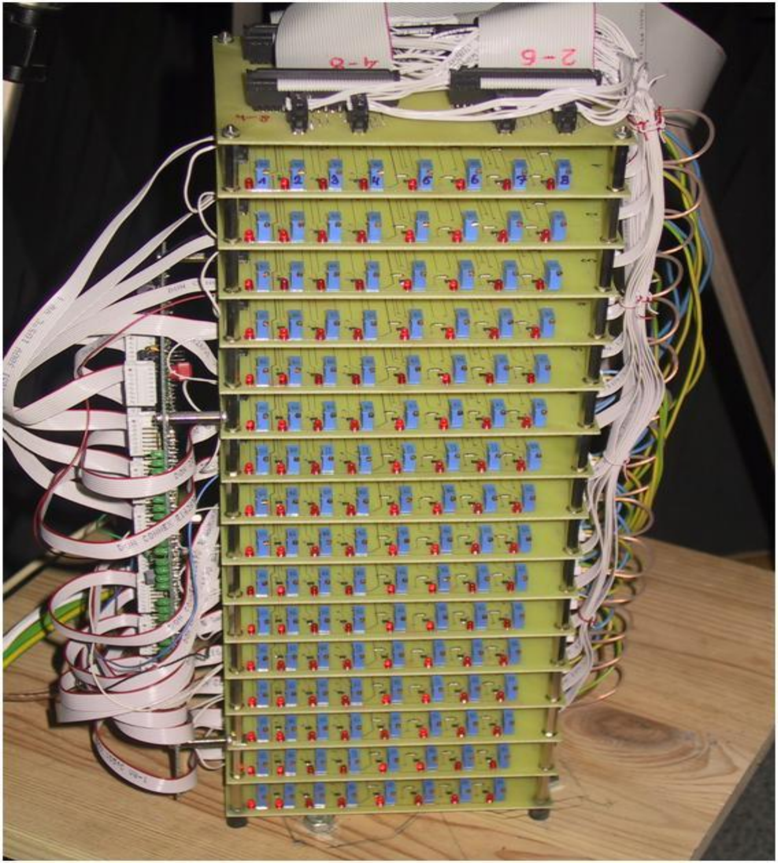


Reconfigurable antenna in anechoic chamber



Steering block of reconfigurable antenna with 128 switches

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Digital Beamforming by using Spatial Multiplexing of Local Elements

The most prominent obstacle to reduce the cost of phased array is the cost of current phase shifter elements.

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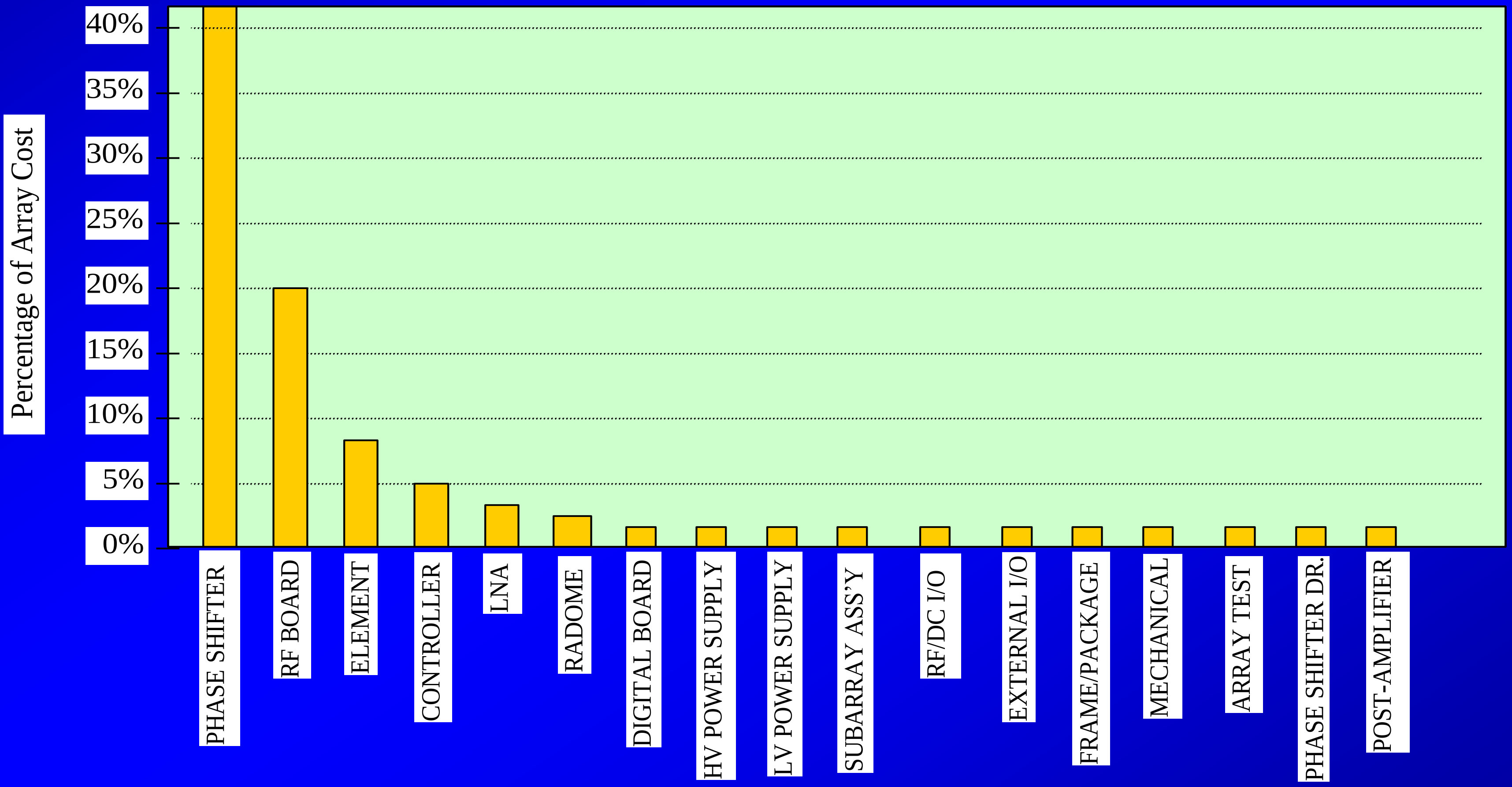

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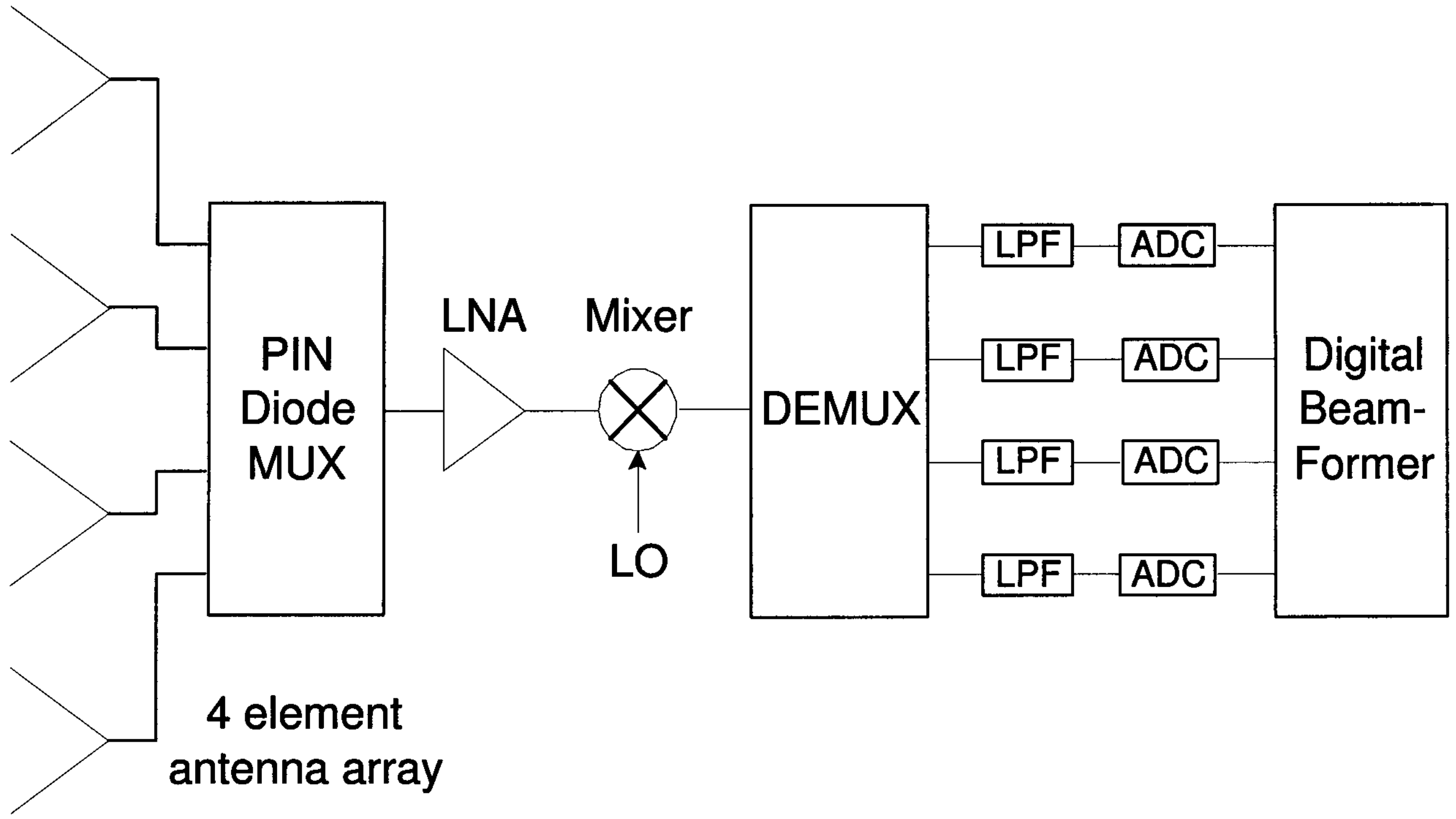
A Smart Antenna Receiver Array Using a Single RF Channel and Digital Beamforming

SMILE – Spatial Multiplexing of Local Elements



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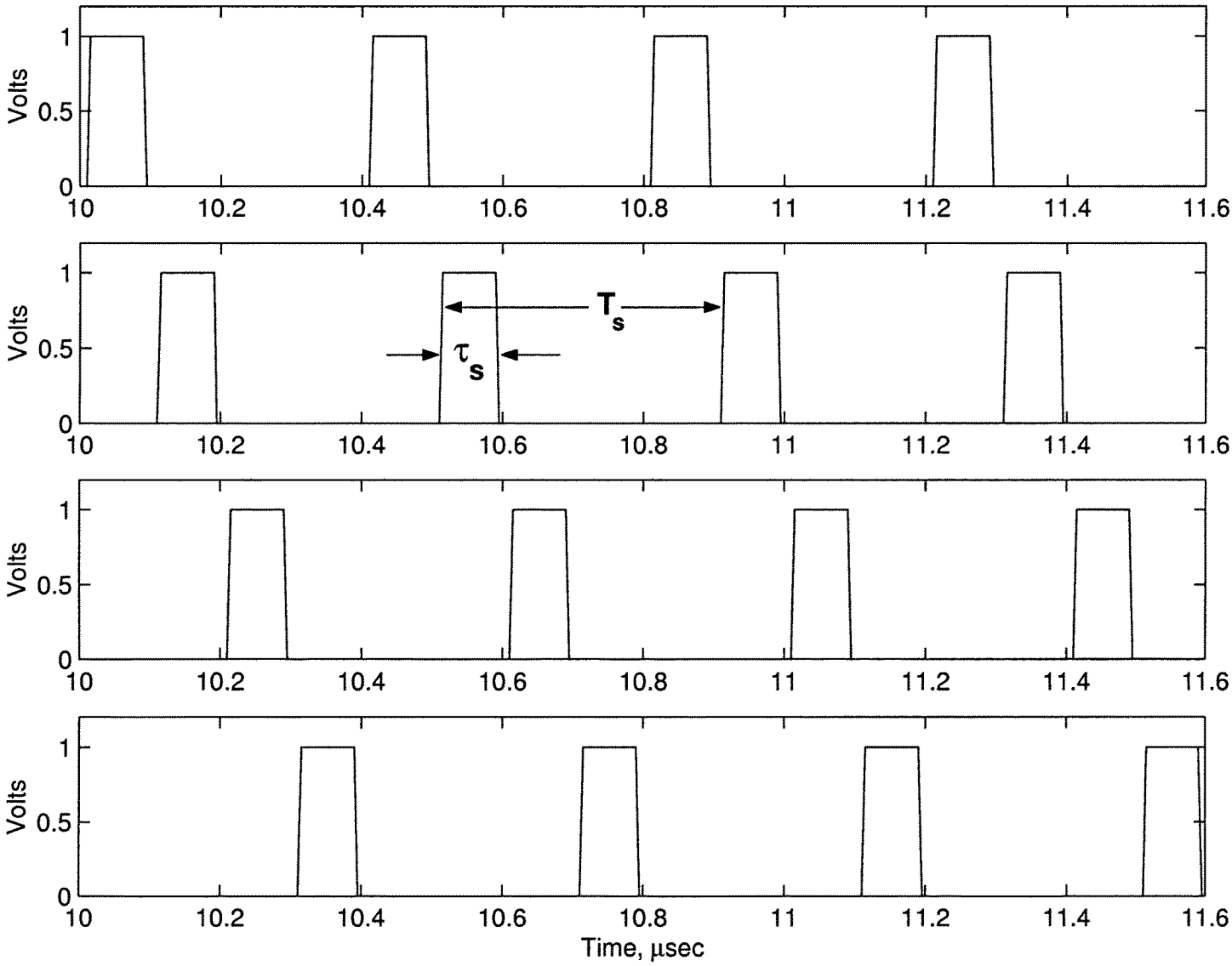
Digital sequence switch timing diagram



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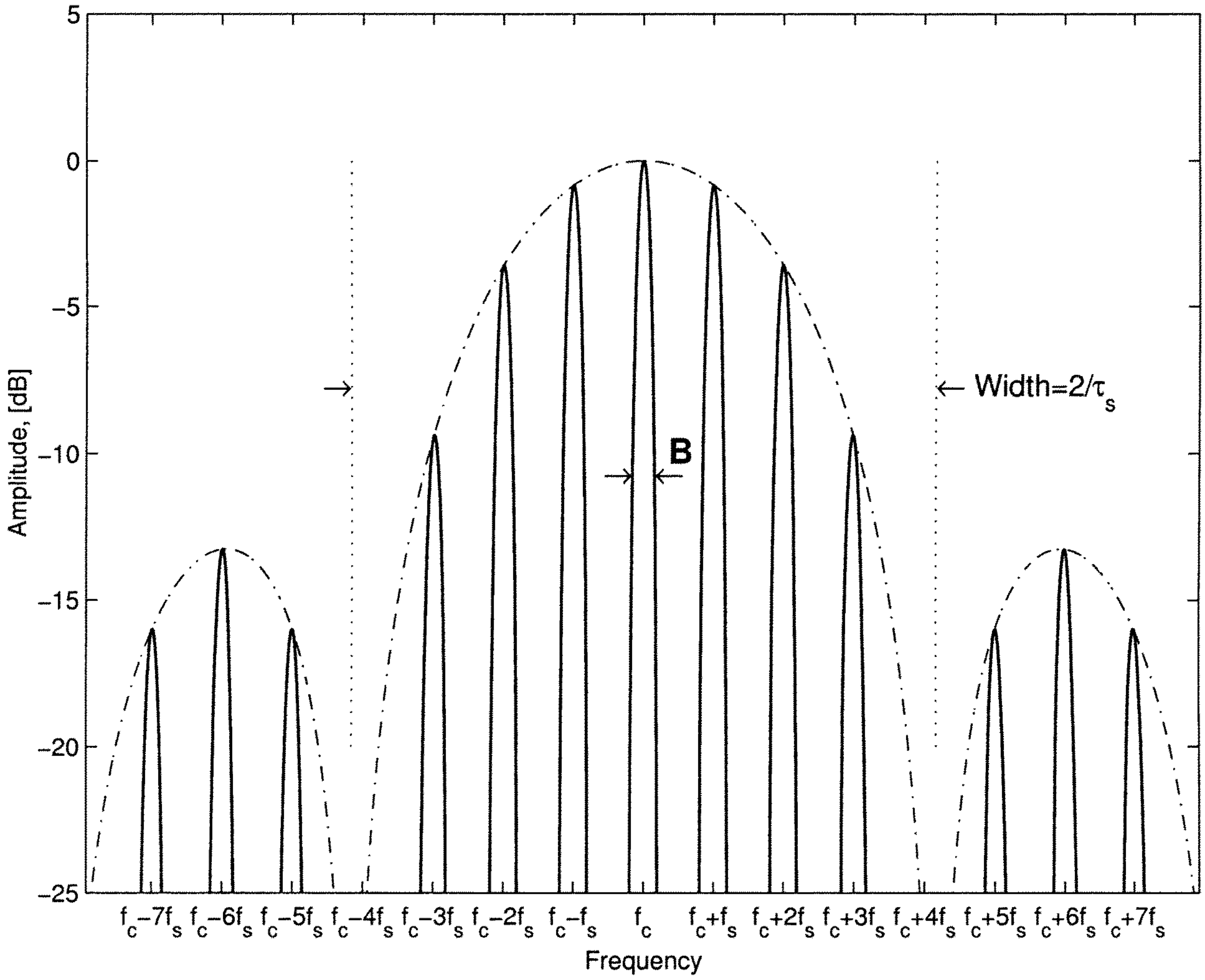
Modulated carrier and sidebands



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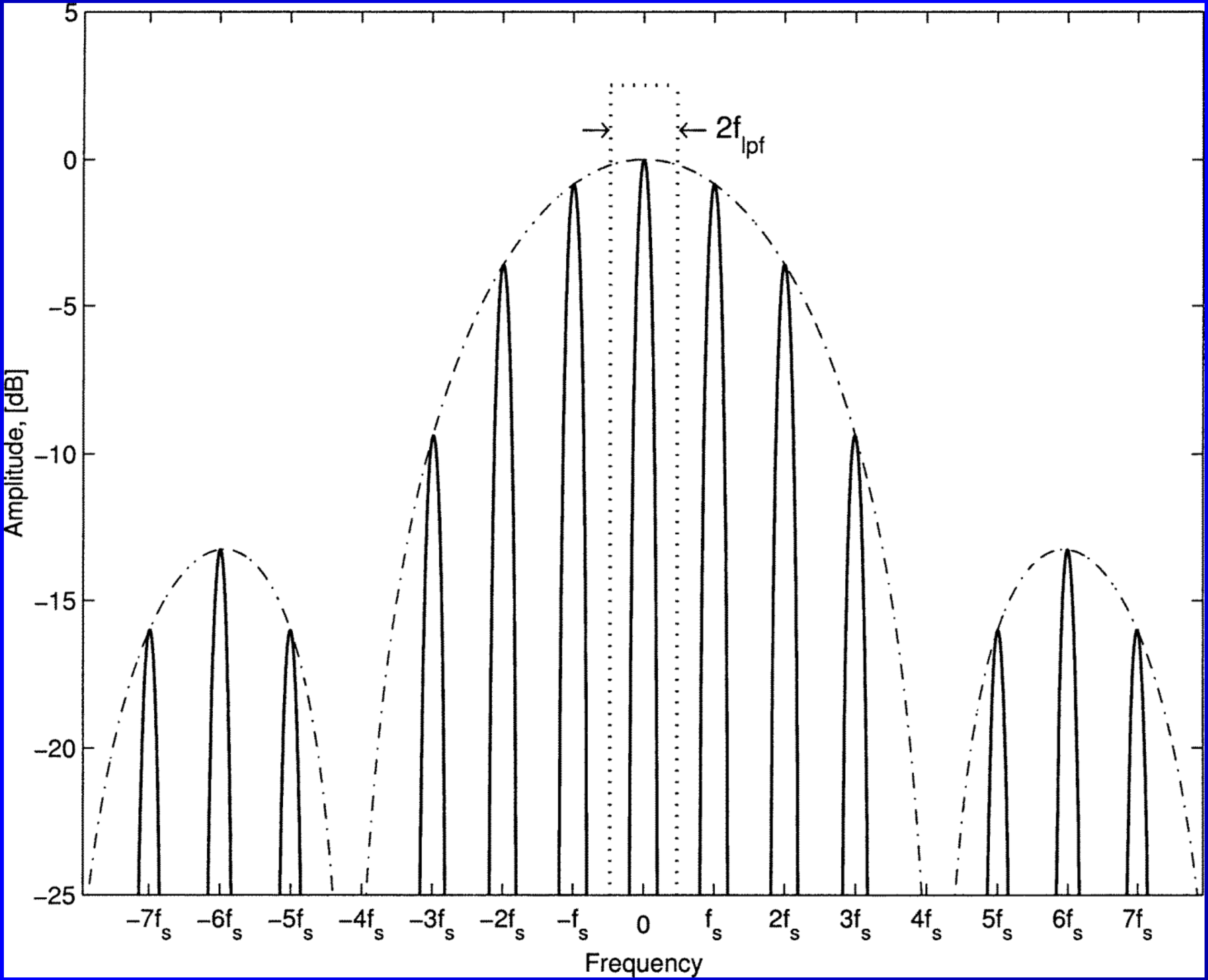
Baseband spectrums with low-pass filter



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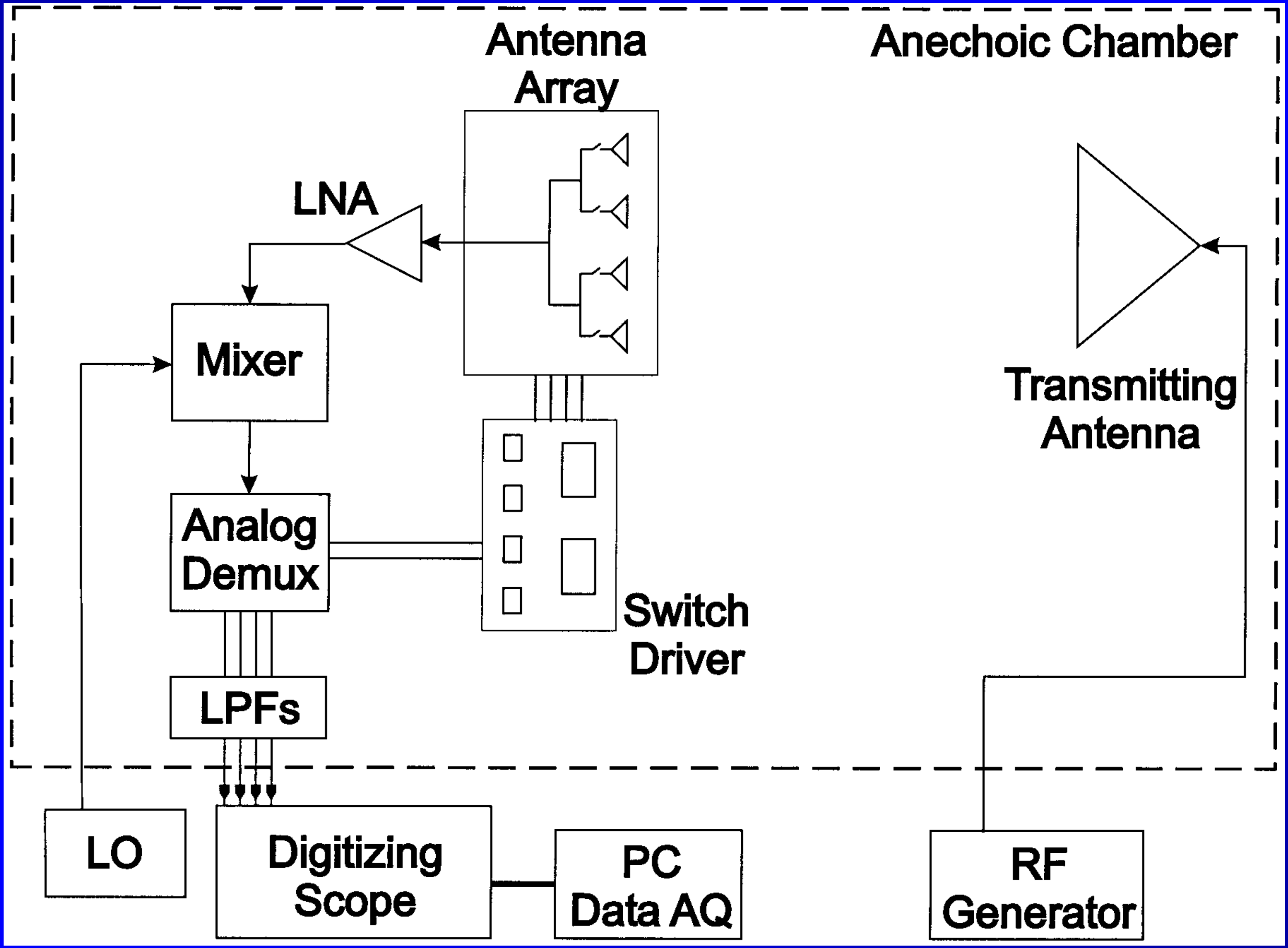
Testbed setup



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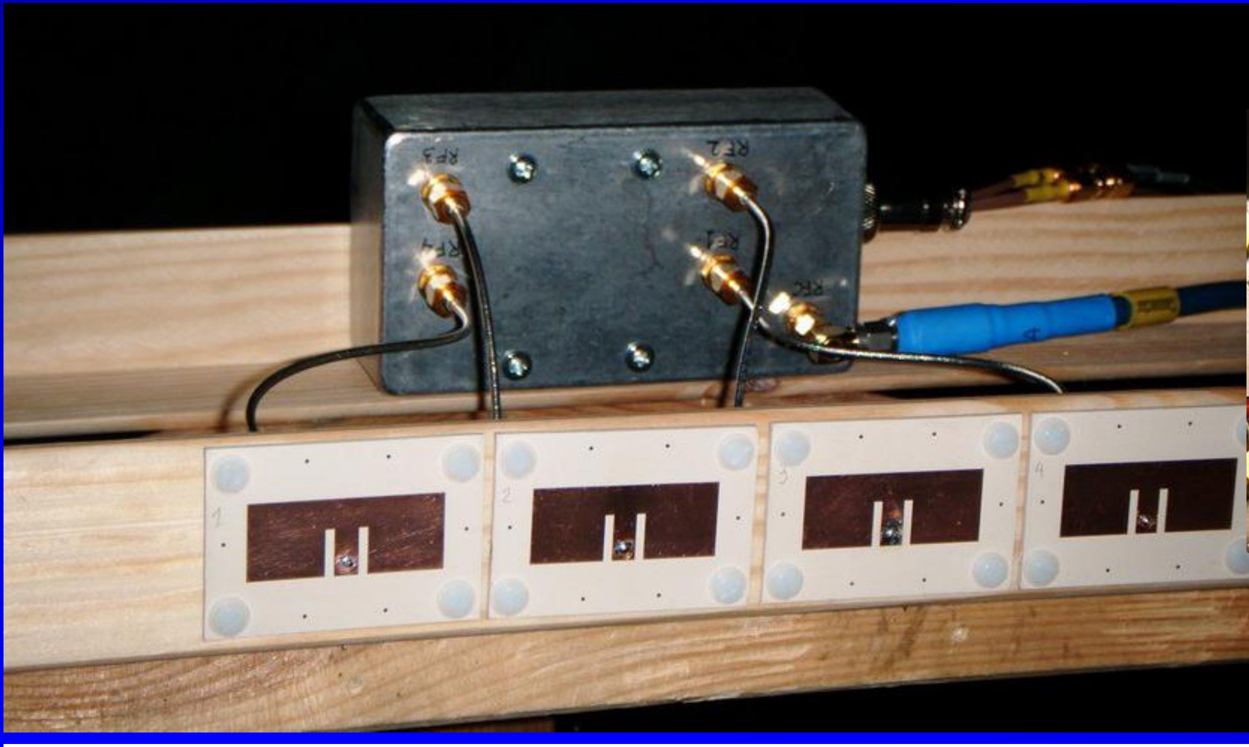
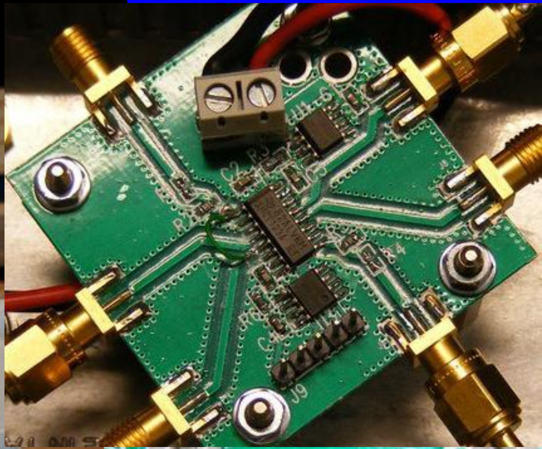
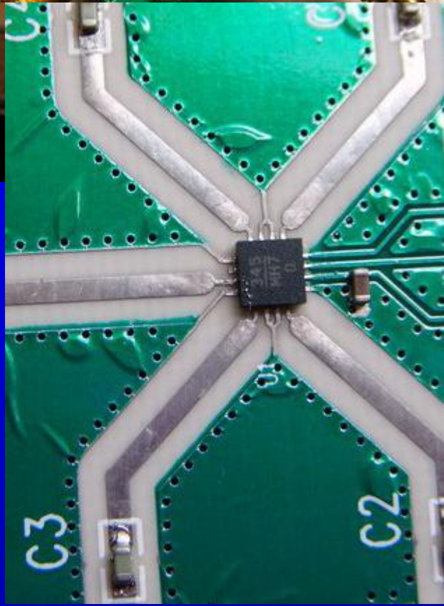
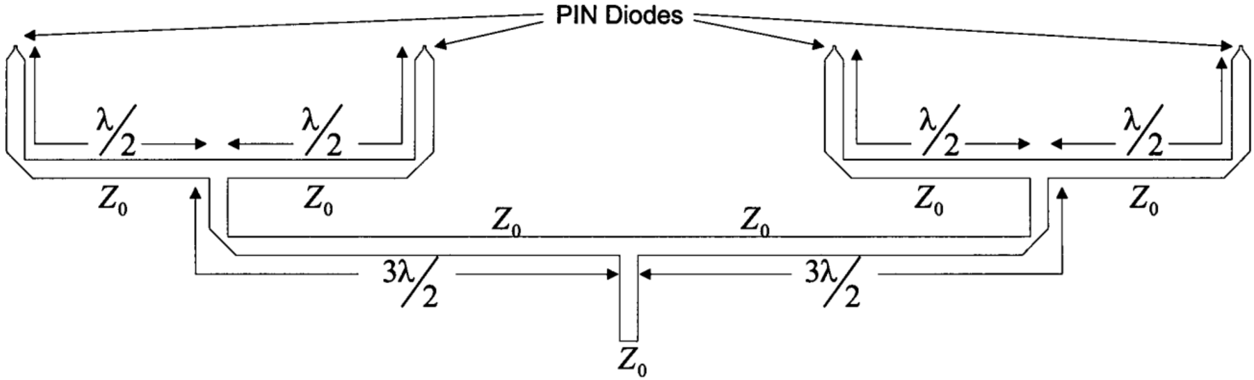
SMILE – Spatial Multiplexing of Local Elements









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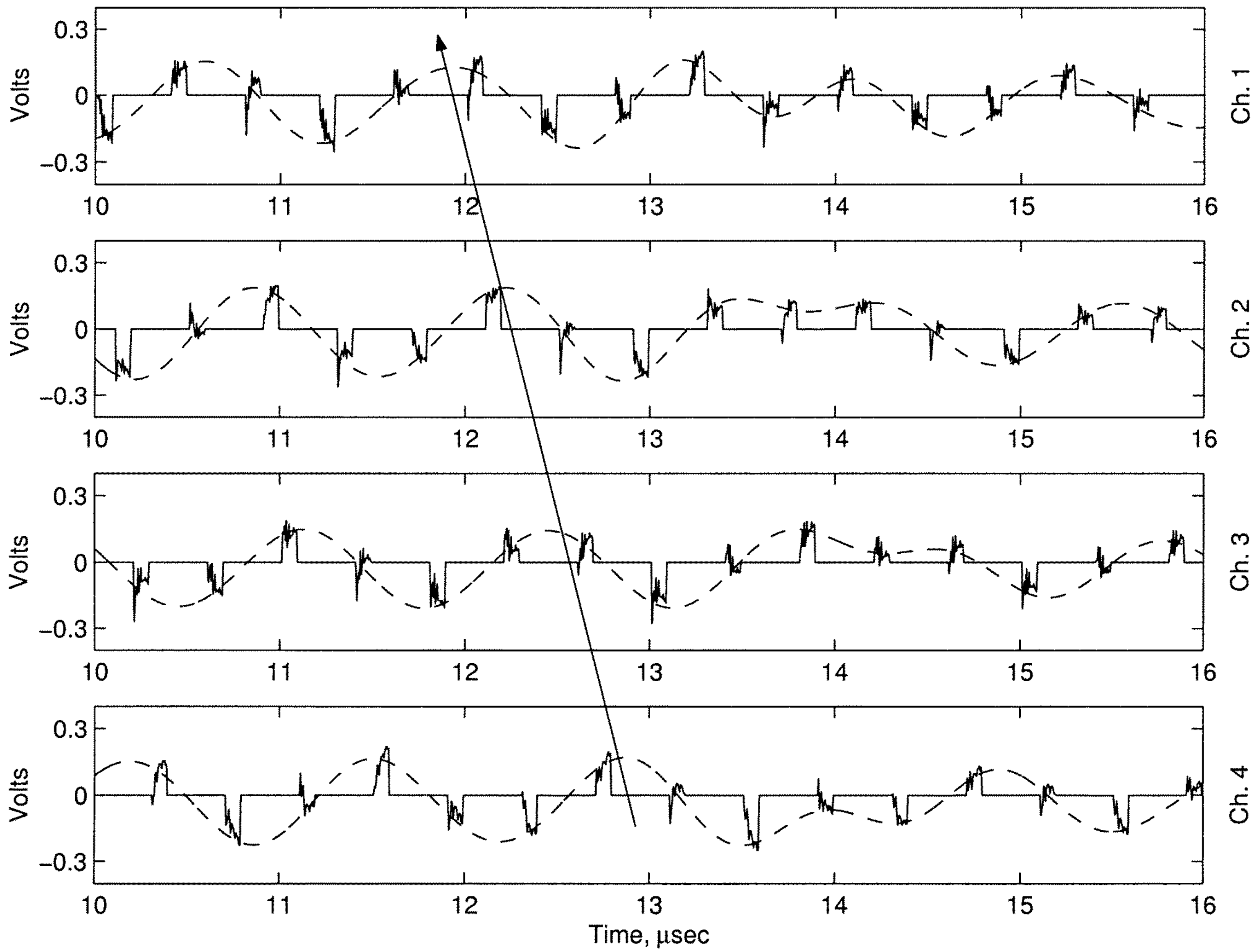
Recovered multichannel baseband data for array at +15^0



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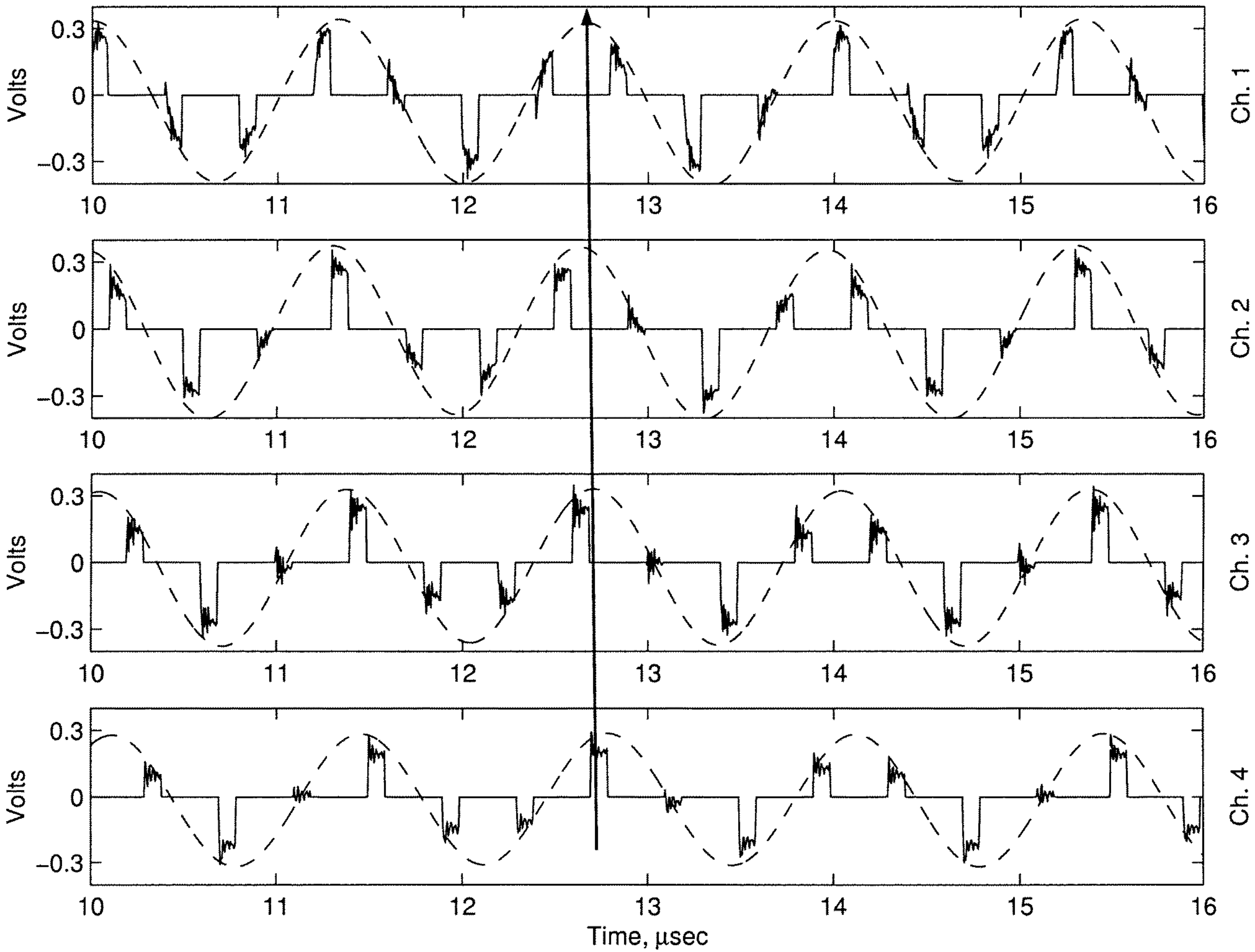
Recovered multichannel baseband data for array at +0^0



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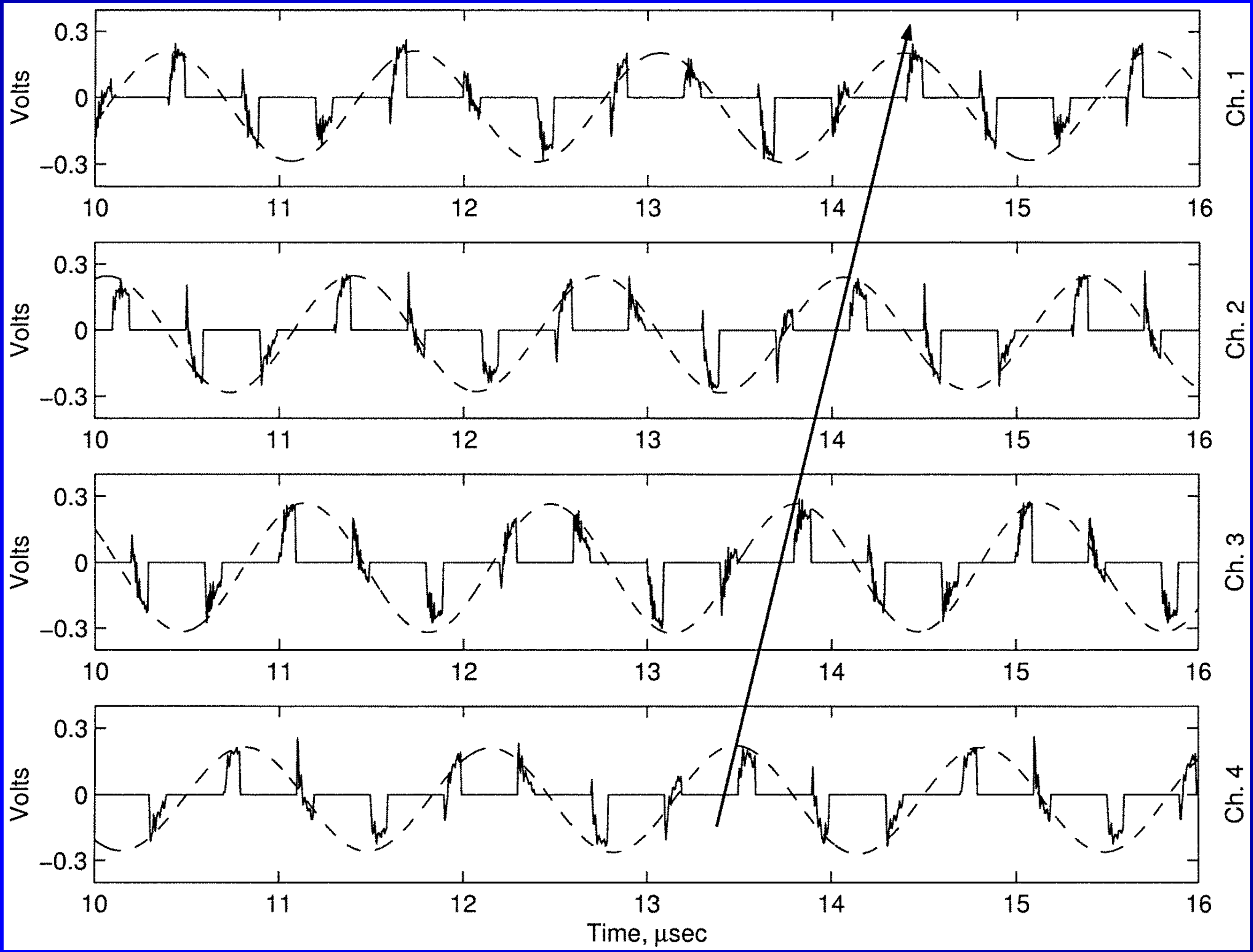
Recovered multichannel baseband data for array at -30^0



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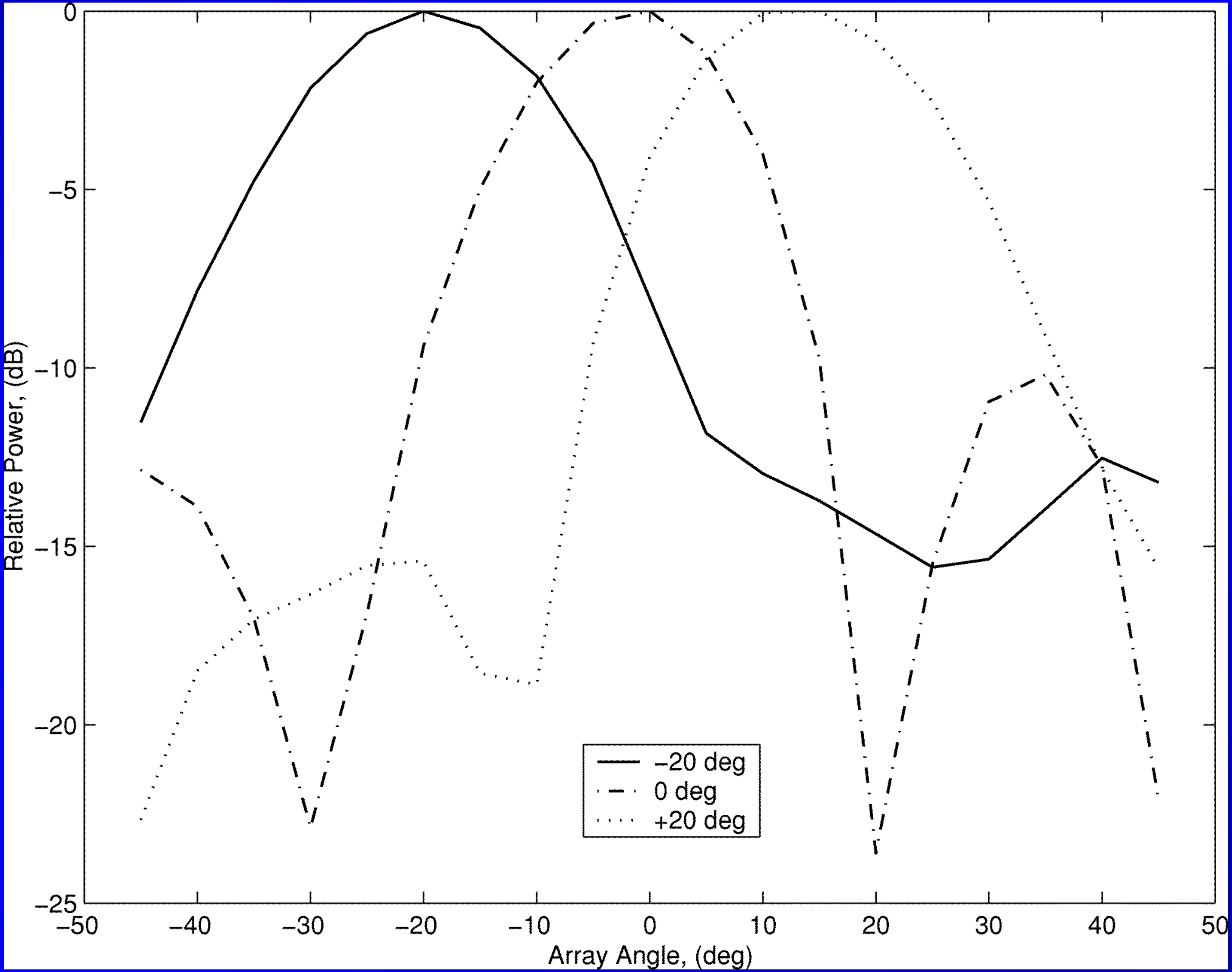
Baseband DBF radiation pattern



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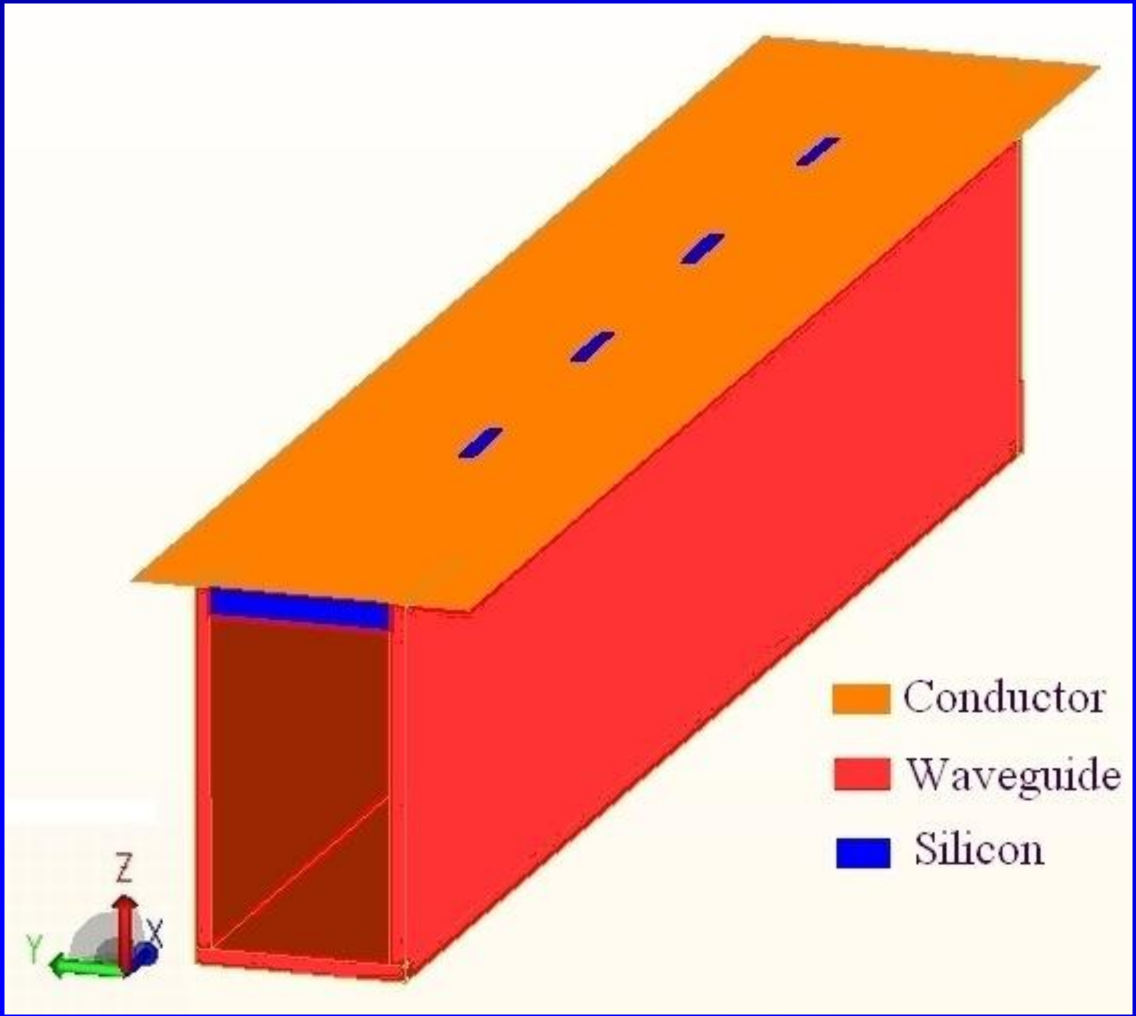
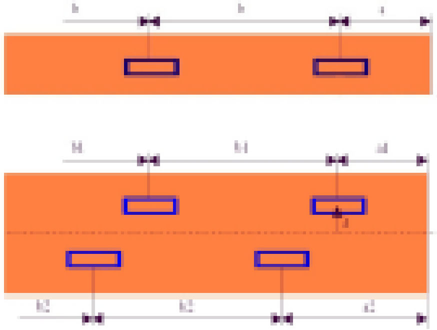
Spatial Multiplexing of Local Elements at mm-wave




The shape of the reconfigurable slot


Two variants of the narrow-wall array slots antennas

Reconfigurable antenna is based on the S-PIN diodes

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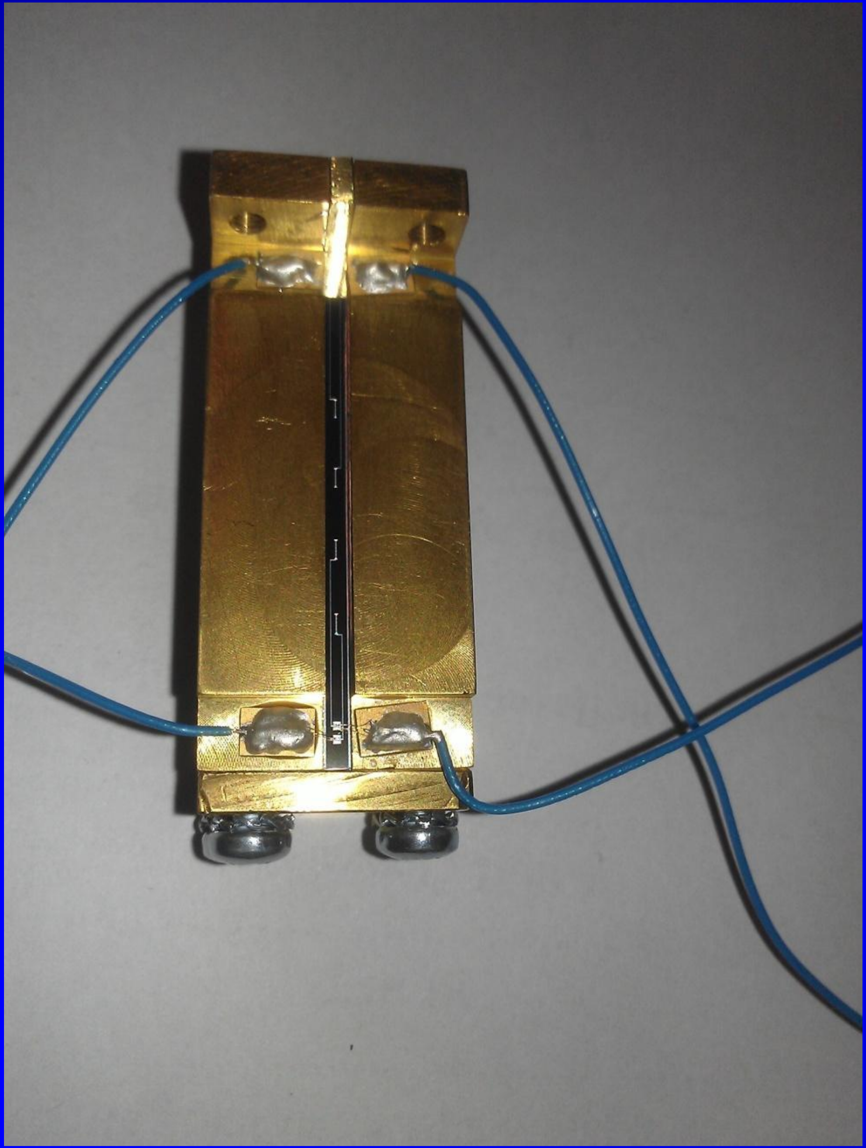
Spatial Multiplexing of Local Elements at 36 GHz



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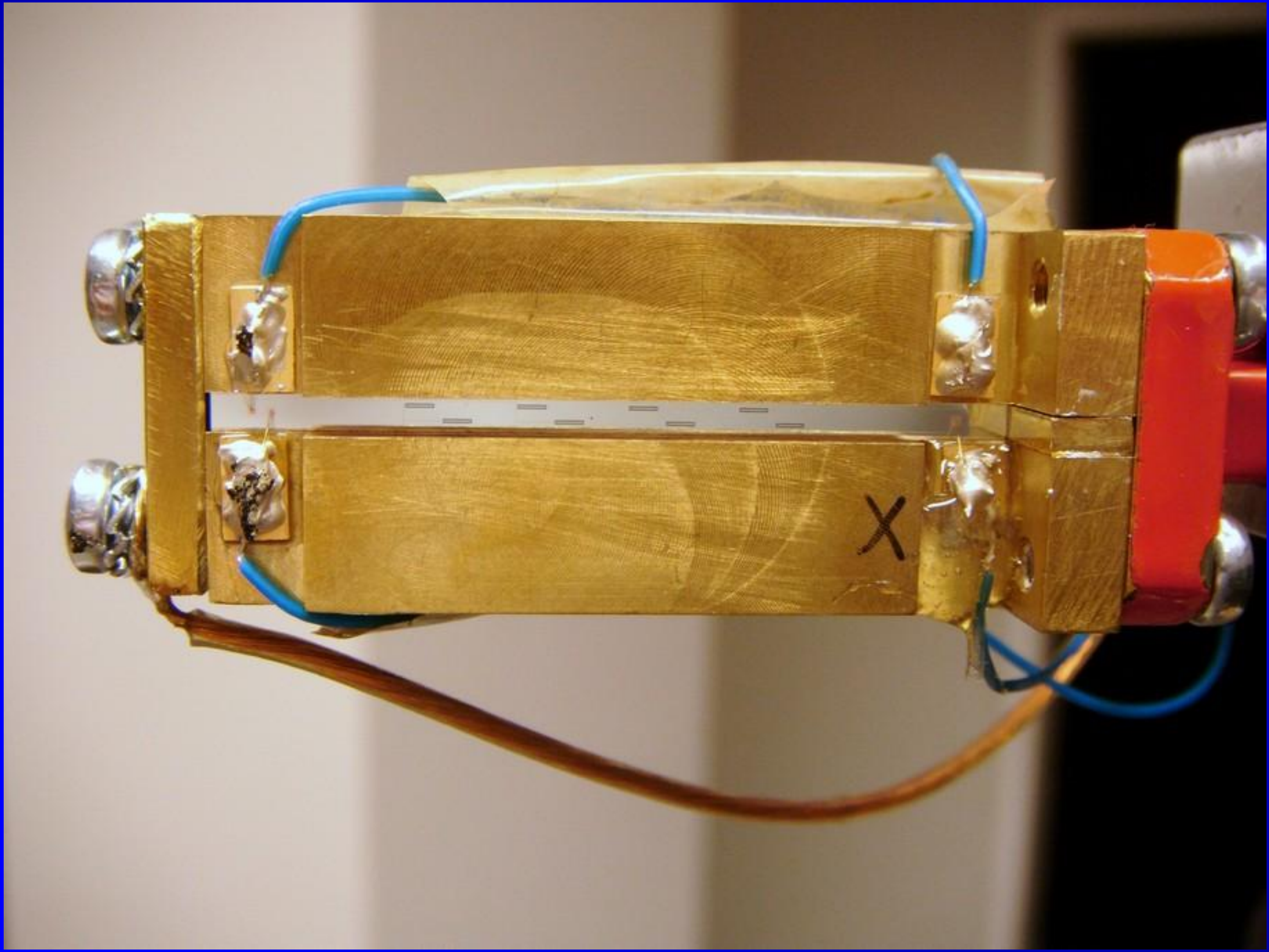
Spatial Multiplexing of Local Elements at 36 GHz



Scenarios of SMILE antenna studies
Frequency of operation - 36 GHz

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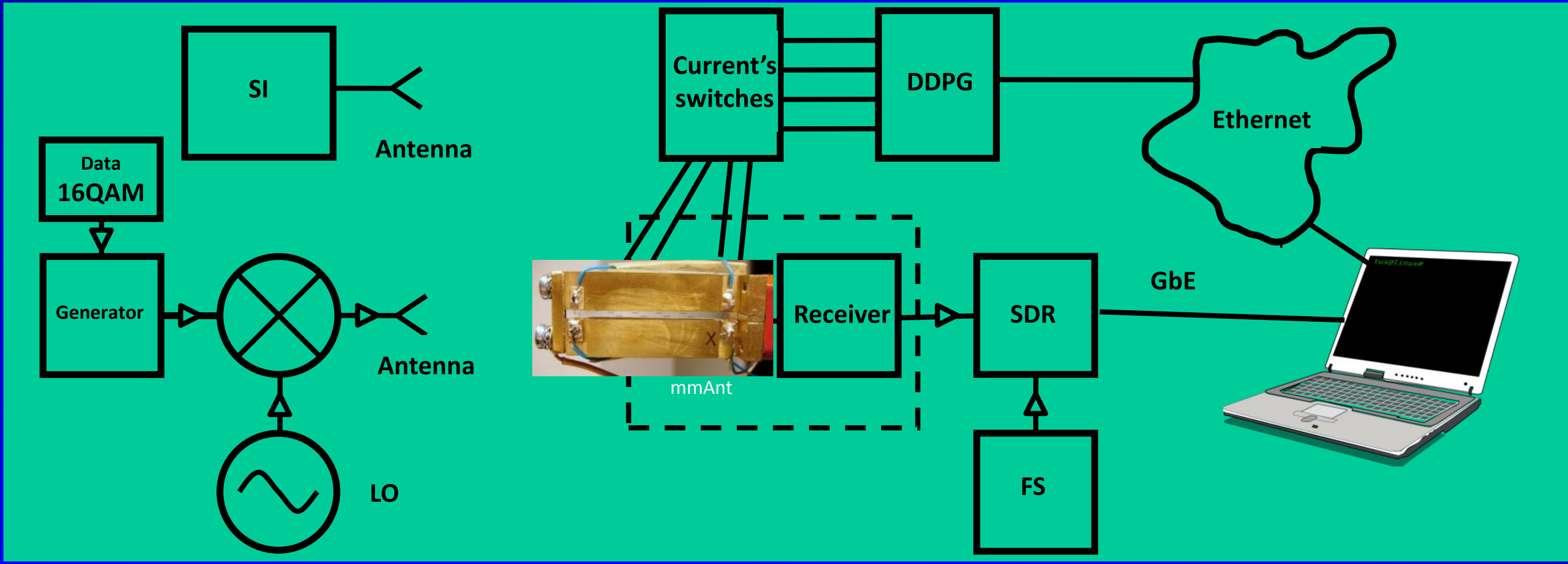
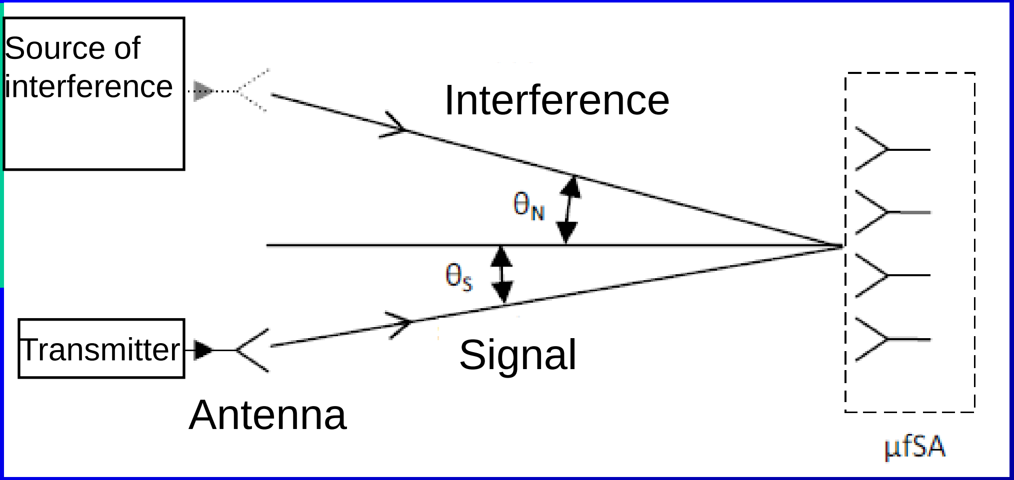


DDPG – Digital Delay and Pulse Generator
SDR – Software Defining Radio
FS - Frequency standard
SI - Source of Interference



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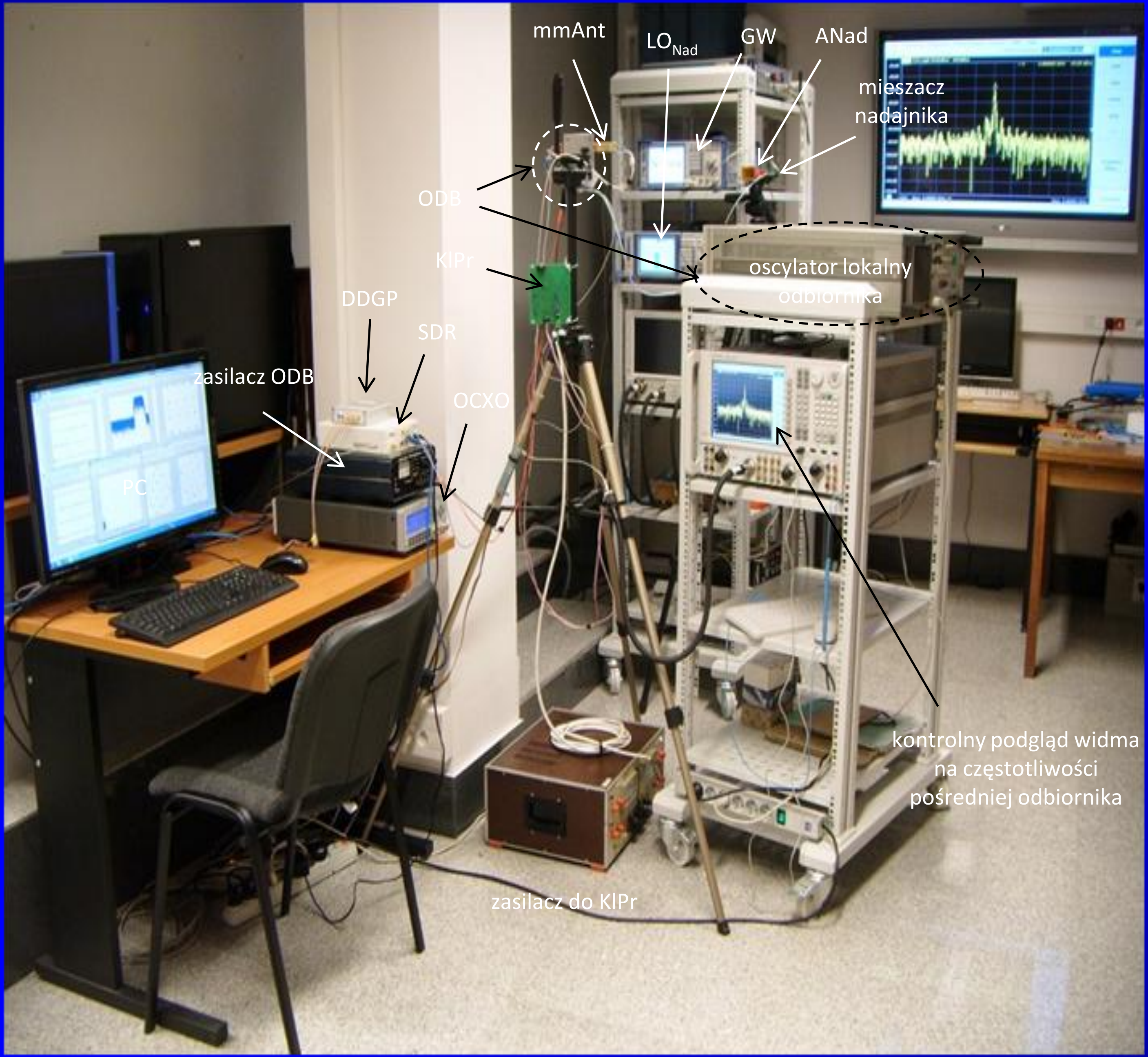

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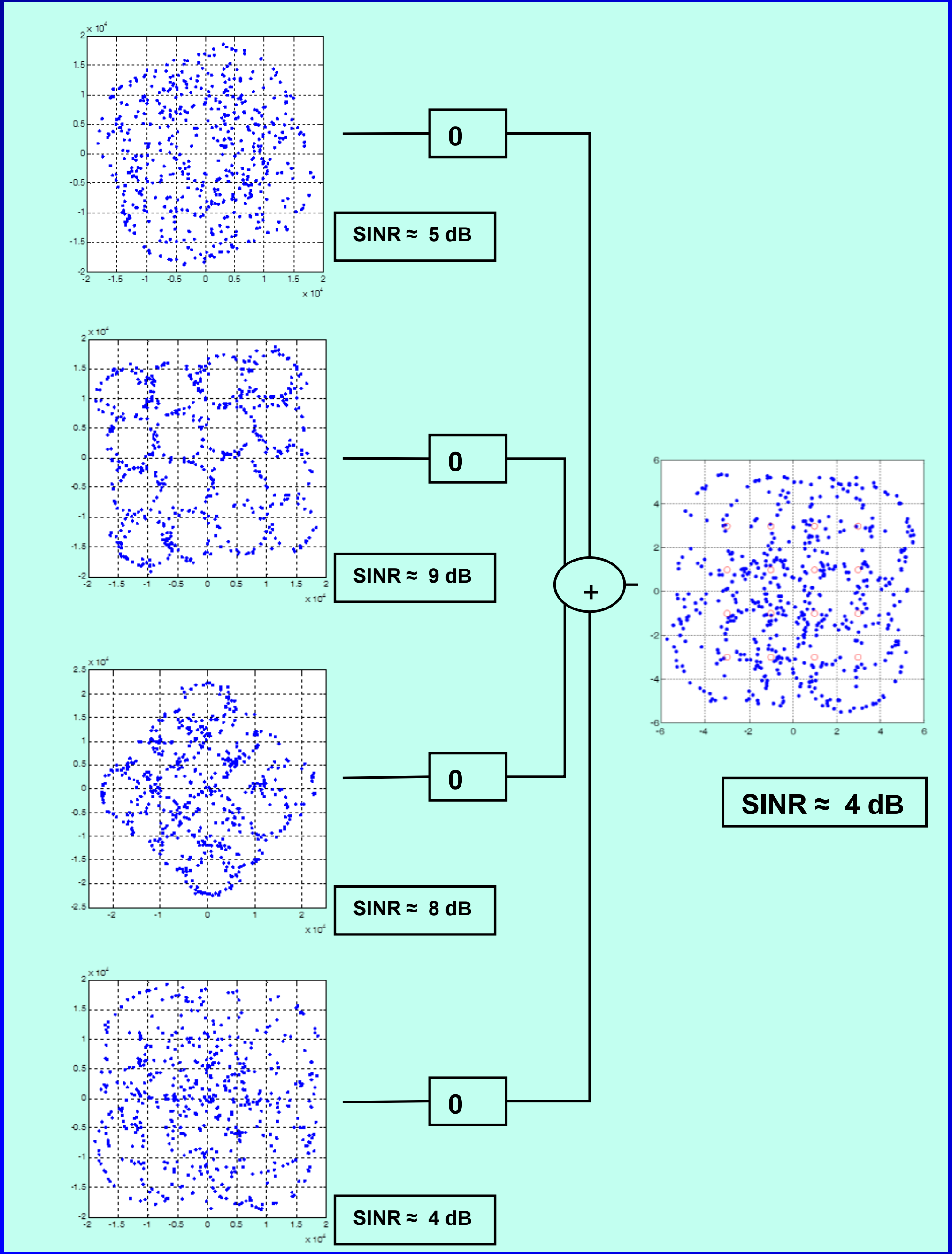
Result of signal summing from 4thchannels without DBF in case of presents of interferences



SINR ≈ 5 dB

SINR ≈ 9 dB

SINR ≈ 8 dB

SINR ≈ 4 dB

SINR ≈ 4 dB

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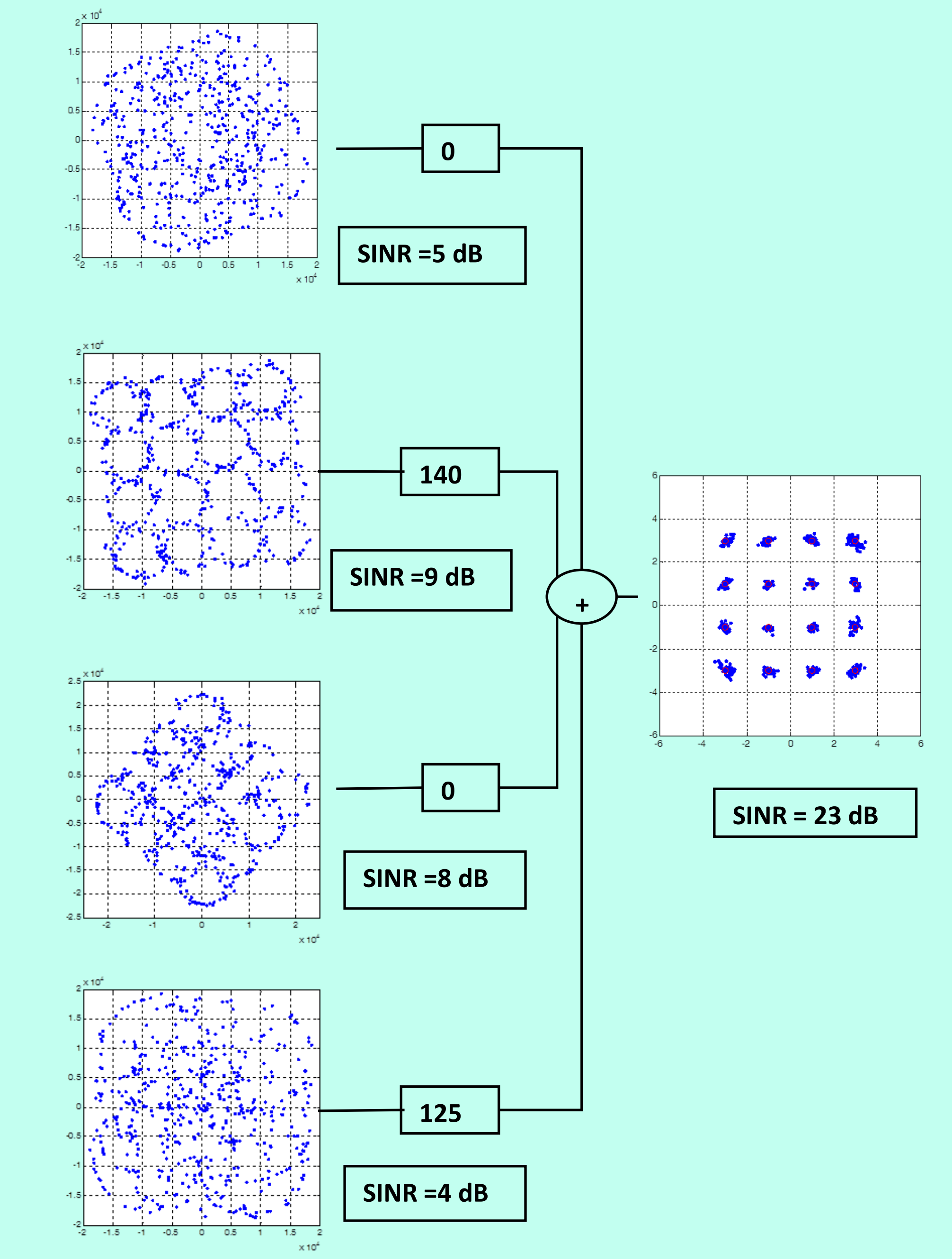
Result of signal summing from 4thchannels with DBF in case of presents of interferences


0

SINR =5 dB

140

SINR =9 dB

0

SINR =8 dB

125

SINR =4 dB

+

SINR = 23 dB

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Conclusion

- ***Providing additional levels of functionality for a wireless system is limited if antenna characteristics are fixed.***
- ***Reconfigurable antenna can help avoid these restrictions***
- ***Using frequency-reconfigurable antennas as an alternative for multiband or wideband antennas is one of the examples of an effective solution***
- ***Spatial Multiplexing of Local Elements for Beamforming is promising***

References

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Thank you for your attention