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Digital Beamforming 2D Antenna for X-band

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Original scientific paper

Our aim is to develop a microwave antenna whose radiation pattern is electronically controlled. The radiation pattern of regular antennas is determined by the Fourier-transform of the complex illumination function on the antenna aperture. This radiation pattern is mechanically fixed so its alteration is impossible. Therefore we construct an antenna system of several antenna elements. All elements are actuated by separate transmitters; we control the amplitude and the phase of the supplying currents of the antenna elements. This way, we are able to control the radiation pattern of the antenna system. The control is computerized so that there is a possibility to change the radiation pattern quickly..

Key words: DBF, DBAS, phase controlled antenna array, smart antenna

1 INTRODUCTION

Smart antennas gain more and more application in modern wireless communication systems thanks to the very important property of spatial filtering. When all the combined TDMA-CDMA systems reach their maximum capacity, the SDMA technique can achieve even higher capacities, such as in MIMO systems, where channel throughput is increased by space-time-frequency combined signal processing [2, 4]. Our goal is to develop and make scientific investigations with a digitally controlled phased-array system. It will be able to shape its direction pattern with almost arbitrary directions of main lobes or null-points without mechanics or inertia. In a two-dimensional rectangular antenna array, with 16 elements, a high degree-of-freedom exists to synthesize very sophisticated radiation patterns. In this paper our approach is presented with both hardware and software solutions.

2 THEORETICAL BACKGROUND

In this chapter we show the theoretical foundation of our beamformer system. We omit the detailed discussion of description, analysis or synthesis methods of antenna arrays but some important relationships will be presented.

Our beamformer is a rectangular antenna array of microstrip patch antennas with the same elementary direction pattern in a uniform array arrangement used only for transmission. To control the overall direction pattern of this array the excitation signal of each antenna element is controlled independently in both amplitude and phase. The resultant radiation pattern is the 2D Fourier transform of the complex excitation values in spatial domain. To adapt the antenna to the actual RF environment, a separate direction finder antenna is needed, wherein adaptive algorithms could be used, and this receiver equipment is able to control the transmitter. For transmission, the task is only controlling the excitation. (In our department, a direction finder receiver antenna which uses adaptive algorithms – e.g. Capon- and MEM-methods – had been developed [1, 2, 3, 5]. We do not use the receiver equipment for the current project, we control the transmitter separately.

Naturally, the radiation patterns of the radiator elements in the array also affect the overall radiation pattern. For the simplest description we assume that the elemental direction patterns are isotropic. Using future measurement results and/or the simulation results of the patch antennas, the controller program is able to calculate on the radiation pattern of the antenna elements. The Fourier transformation explains how can the properties of the radiation pattern be controlled by the currents feeding the antennas. For example to achieve a lower side-lobe level, the weighting of the excitation amplitudes must be decreased towards the borders of the antenna array, so we apply a window-function.

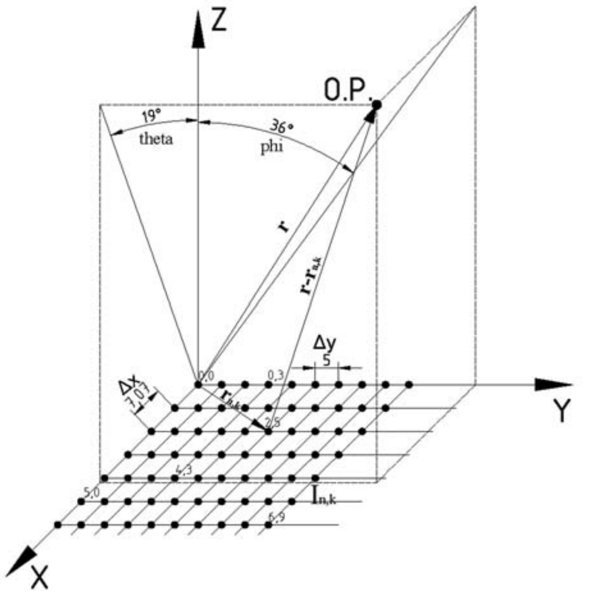

Fig. 1 Berth of the rectangular antenna array in a Descartes coordinate system

To obtain the far-field radiation pattern of a rectangular antenna array equation (1) must be evaluated. The number of antenna elements is 16 in 2D. So, n and k run from 0 to 3, β is the wavenumber, Δx and Δy are the distance between antenna elements (2), $I_{n,k}$ is the complex value of the excitation current of the n,k-th antenna element, $F_e(\vartheta,\varphi)$ is the elementary antenna factor – see Figure 1.

$$F(\vartheta,\varphi) = F_e(\vartheta,\varphi) \cdot \sum_{n=0}^{N-1} \sum_{k=0}^{K-1} I_{n,k} \cdot e^{j \cdot \beta \cdot e_r \cdot r_{n,k}^T}. \quad (1)$$

Where $\boldsymbol{r}_{n,k}$ is a vector from the n,k-th antenna element to the observation point (2), and $\boldsymbol{e}_r$ is a unitvector to the observation point (3).

$$r_{n,k} = [\Delta x \cdot n,\ \Delta y \cdot k, 0] \quad (2)$$

$$e_\mathrm{r} = [\cos\vartheta \cdot \sin\varphi,\ \sin\vartheta \cdot \sin\varphi, \sin\vartheta]. \quad (3)$$

Contrary to conventional antennas, we can define degrees of freedom with antenna systems, which is equal to $2NK$. We are able to adjust the main radiation direction, the side lobe level, null-points and the main lobe width by controlling the phase and the amplitude of the excitation of the antenna elements.

2.1 Controller Software

Our simulation and controller software is presently capable of evaluating the direction pattern of a rectangular array of uniformly spaced antennas with a maximum element number of 16. The software is written in LabView, a screenshot of it can be seen in Figure 2. The element distance and main radiation direction are variables. The excitation amplitudes and phases of each element are adjustable independently. Some built-in predefined illumination functions are available, such as binomial, triangular, equal amplitude, etc.

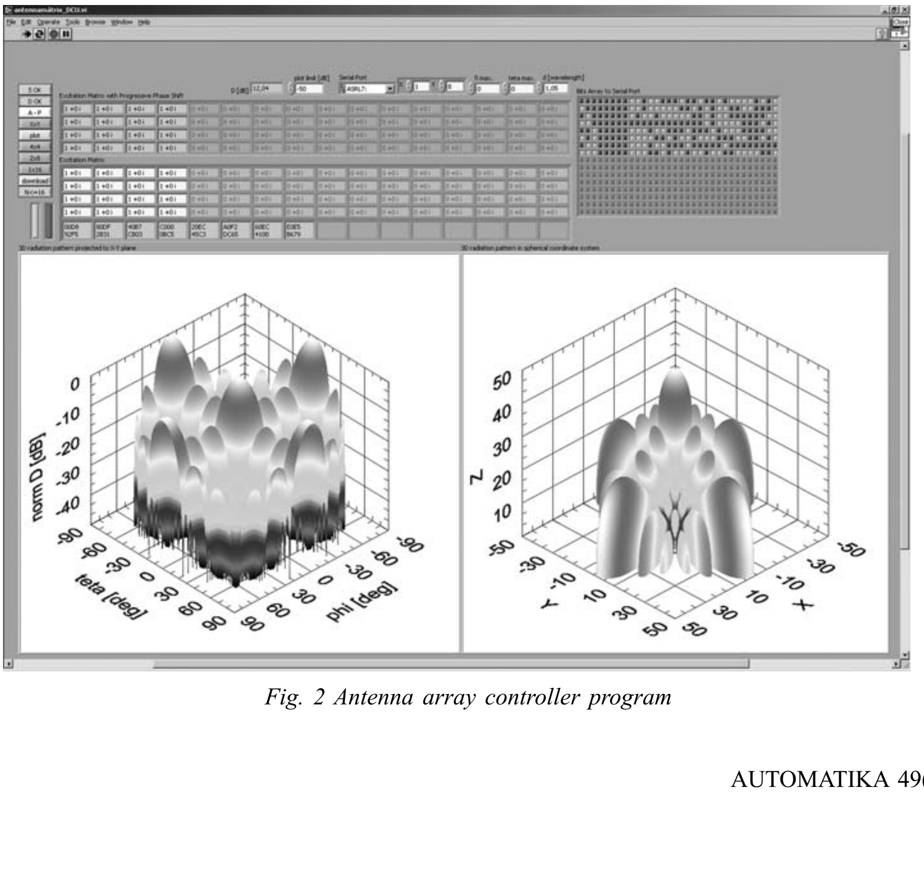

Fig. 2 Antenna array controller program

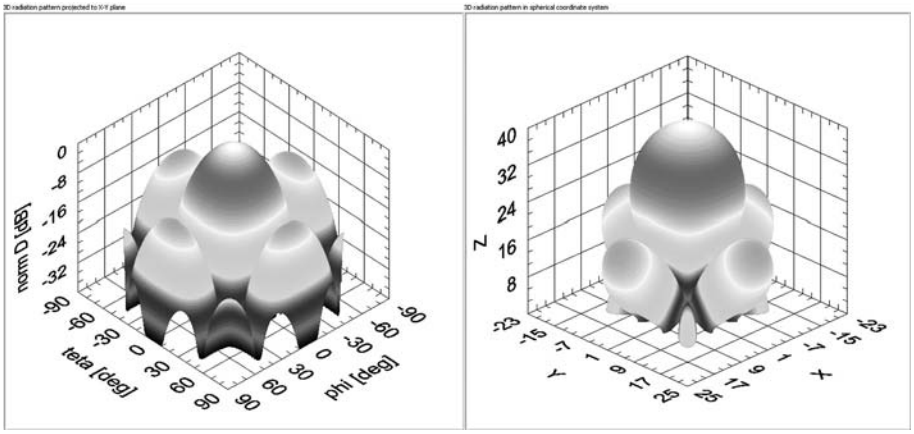

Fig. 3 Analyzed radiation pattern of 4x4 antenna array

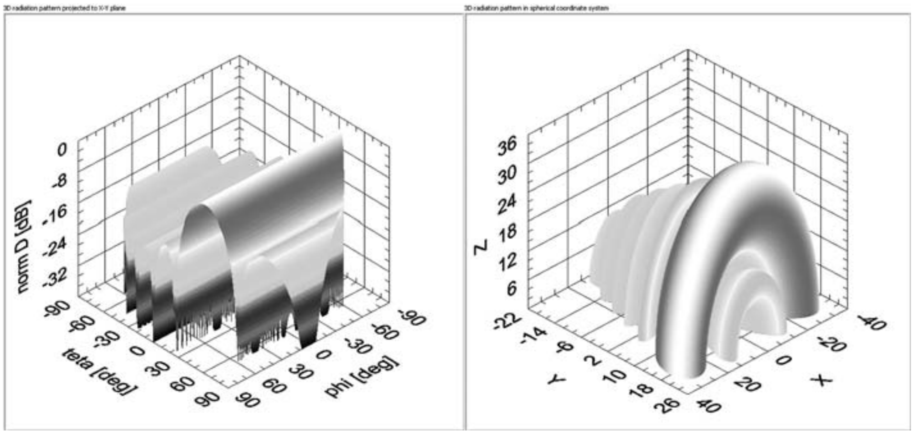

Fig. 4 Linear antenna array with 8 elements

According to the excitation matrix and the main radiation directions, the controller program calculates the 2D radiation pattern. See Figure 3, where the distance between antenna elements are half wavelength, both in X and Y dimensions, and the main radiation directions are 0 degree (both in ϑ and φ). On the left is the 3D radiation pattern projected to ϑ,φ plane; on the right is in spherical coordinate system (this is the real 3D radiation pattern).

If we use only 8 antenna elements in 1×8 arrangement, it will be symmetric around axis Y – see Figure 4, where the $\Delta y = \lambda/2$, and $\vartheta = 30°$.

The software is able to download the calculated excitation weighting matrix into the beamformer hardware via serial port.

2.2 Hardware Description

There are many constructional aspects about the hardware design of a digital beamformer antenna array. The goal is to implement a complex multiplicative weighting on the separate transmitter channels. To achieve this it is necessary to control the amplitude and phase of the excitation signal of each antenna element. It is possible to feed more antennas with the same signal. For a higher level of flexibility our design is capable to control 16 antenna elements independently. Two possible approaches exist for the implementation of the complex weighting, a »true digital« and a »quasi digital« design.

The »true digital« way does all signal manipulation with digital signal processing, producing or processing the signals at the complex baseband or at an intermediate frequency. It needs high-speed computing solutions, and for increasing element numbers and increased signal bandwidth it needs even higher speed or distributed processing. This means higher cost, but as DSPs and FPGAs develop, it will become more and more cost effective. The dynamic range of the transmitted signals is

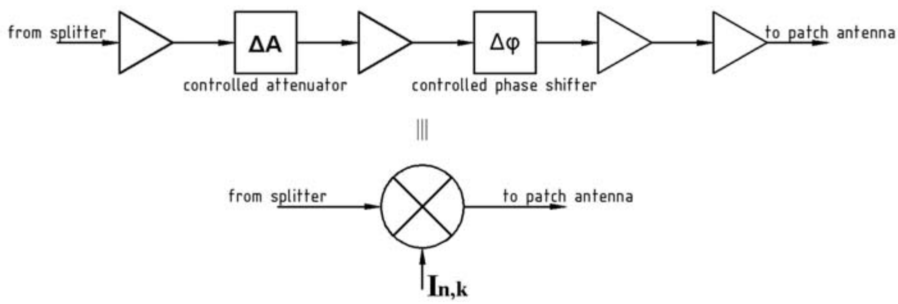

Fig. 5 Build of a 10 GHz transmitter channel

limited by the digital calculation precision and the quality of analogue-digital converters, so it can have a very high level of dynamics. The digitally processed or produced signal then passes to the upconversion and RF amplifier stages. If the upconversion is also made digitally on an intermediate frequency, only the IF-RF upconversion, RF amplification and the radiator element can cause unwanted radiation pattern variation by amplitude and phase errors or elemental direction pattern differences. Moreover, these effects are hard to manage because those depend on temperature and frequency.

The »quasi digital« way is to make the proper amplitude and phase control directly on the upconverted RF signal by digitally controllable attenuator and phase-shifter circuits. In this way no high-speed real-time signal processing is needed until a true adaptive fading reduction or target tracking must be done. The bandwidth could be higher than in real-time baseband processing, because the carrier frequency is also high, and the control of the signal properties (amplitude, phase) is done by relatively slowly changing signals.

The common problem of the two different approaches is the calibration of the transfer functions of the transmitting channels versus temperature and frequency. That can be done by a feedback loop during operation or by storing a huge calibration database in memory and compensating the amplitude and phase errors of the RF circuits.

The realization of a transmitter channel is shown on Figure 5 – the complex multiplier is realized by controlled attenuator and controlled phase shifter.

The connection diagram of a four-channel transmitter block is shown on Figure 6; the digital con-

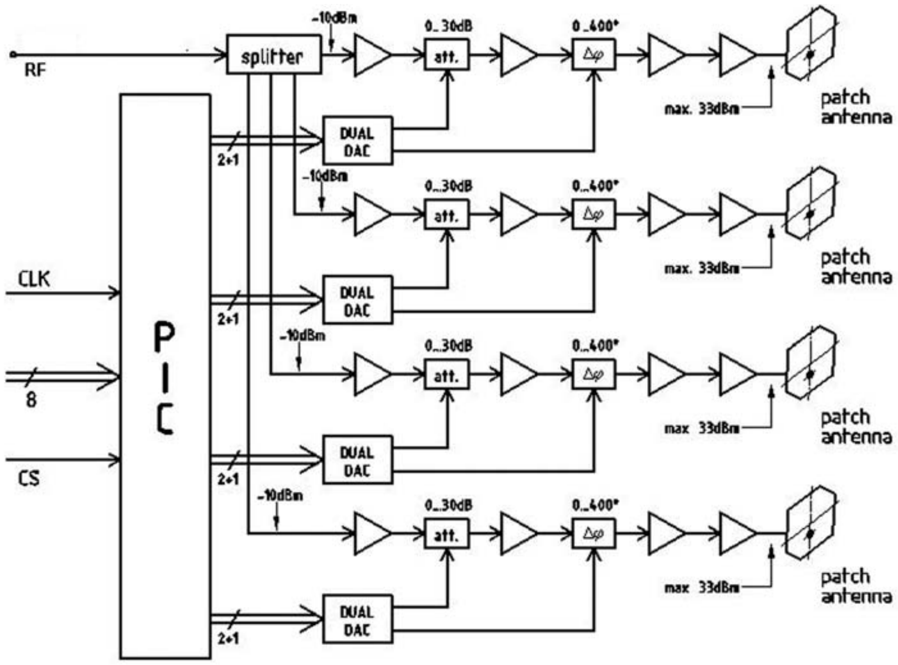

Fig. 6 Connection diagram of a four-channel transmit block

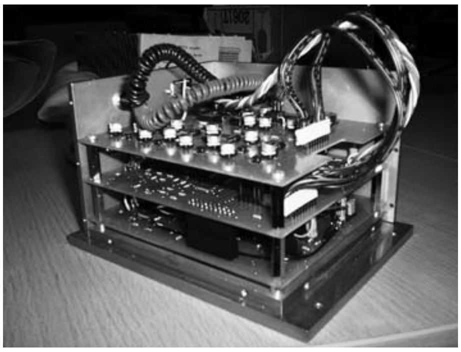

Fig. 7 Digital control unit

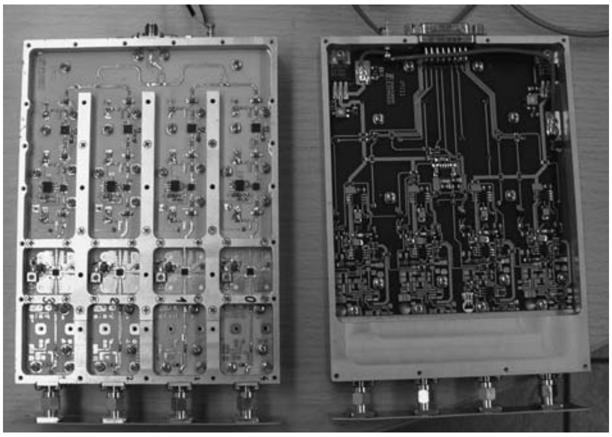

Fig. 8 Four-channel transmit blocks

trol unit (including microcontrollers, D/A converters, line-amplifiers and serial adapter) is shown on Figure 7; RF unit (including splitters, attenuators, phase-shifters, RF amplifiers) is shown on Figure 8.

The microwave RF signal is split and fed into a chain of attenuators and phase-shifters which have analogue control inputs. Amplifier stages are used to achieve the desired gain and power level and isolate the attenuator and phase-shifter stages. Digital control of signal properties is achieved by D/A converters and on-board microcontrollers. The controller software downloads the weighting vector components and the microcontroller produces the proper analogue signal. The radiators are microstrip patch antennas with linear polarization.

The controller software is able to control the hardware to realize one or more different radiation patterns, to switch over among them and to scan in given angle range several times per second. To switch over, it is necessary to give the different complex weightings for each radiation pattern (64 byte/radiation pattern), to scan it is necessary to give the first and last angle of scanning and number of steps. The controller software is able to calculate and download them into the digital controller unit, then the computer can be disconnected from the controller. Thus the antenna system can run independently of the computer. In each radiation pattern, the main lobe direction, side lobe level and suppression are determinate. For one or more directions, the antenna can match null-points not to cause interference or disturbances for other radio systems.

2.3 Calibration process

Calibration process is necessary because the phase shifter attenuates according to its phase shift, and the attenuator shifts the phase according to its attenuation and these are non-linear versus the controller voltages.

The amplitude and phase shifter control voltage range is 0..+/–2,5V in 12 bits. So, there are 4096 points both in amplitude and phase, the total number of S_{21} to be measured is more than 16 million. Accordingly automated measuring process is necessary.

The calibration program stores the current values of the amplitude and phase data to the digital control unit, controls a HP vector network analyzer and receives the measured complex S21 data – see Figures 9 and 10.

If the desired transfer function of the first channel is 0.5 and 30 degrees, the task is to look this complex value up from the 3D calibration matrix, and store its coordinates to the digital controller unit (these coordinates are the amplitude and phase controller voltages) – in this way, the practical

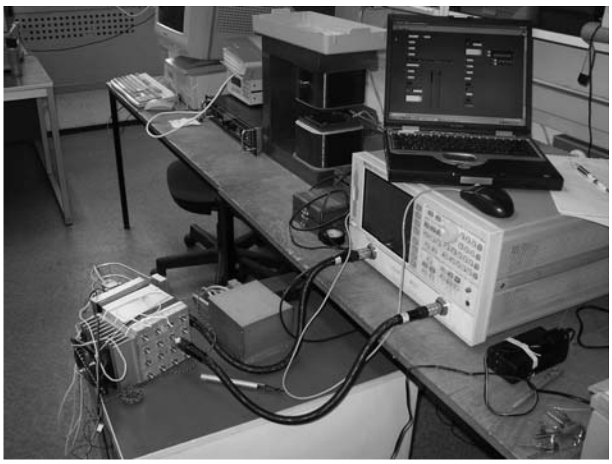

Fig. 9 Calibration measurement of the 16 channel rectangular antenna system

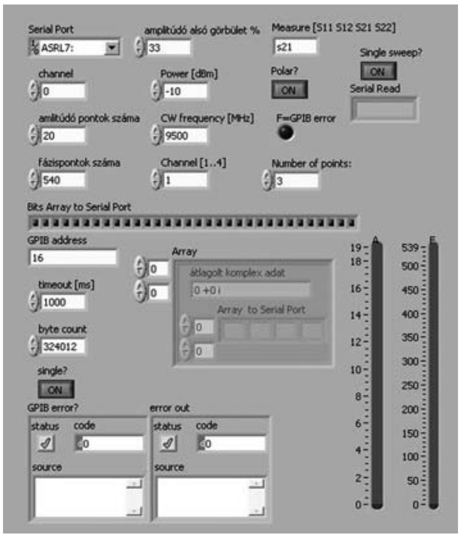

Fig. 10 Calibration program

value of the transfer function will be close to the desired (this closeness depends on the number of the measured points).

Note that if the measuring time of one point is only 10 ms with computerized measuring, the whole calibration would take about 2 days per channel (the calibration of the whole antenna system would take about 16 days). Instead we measured in 20 amplitude and 540 phase points, and then we used 2D complex interpolation.

The antenna controller program – which is shown on Figure 2 – uses these complex element 3 dimensional databases. Its task is to look the right S_{21} element up from this database and send its coordinates (control voltages of amplitude and phase) into the DCU.

The amplitude and phase non-linearity versus control voltages is highly visible on Figure 11. The further calibration matrices are similar to it.

2.4 Measurement results

We measured the radiation patterns of a 2D 16--channel rectangular transmitter antenna array, where the distances between antenna elements are 1.05 wavelengths both in X and Y dimensions – there are technological reasons why we are not able to decrease the antenna distance arbitrarily. (The optimal antenna distance would be half wavelength, but we cannot make channel with 15 mm width, because the width of amplifiers, phase shifters and attenuators on the PCB is more than half wavelength.) Thanks to the 1.05 wavelength antenna distance, there are grating lobes, but this is not a serious problem, because we use microwave patch antennas. First, this elementary antenna has own radiation pattern where the main lobe width is about 70 degrees, so it is able to filter the grating lobes out as a spatial filter. Second, the scanning range with the main lobe of the antenna system is about 60..70 degrees, and in this range, the second main lobe is invisible.

The antenna system was mounted on an rotatable antenna pedestal to measure its radiation pattern, shown on Figure 12. An anechoic chamber for antenna measuring is needed, where the walls are coated of microwave occlusive material to be able to measure the far-field radiation pattern.

Antenna-distance is 1.05 wavelengths; frequency is 9500 MHz, input power is 0dBm. We adjusted 2D constant amplitude distribution and zero degree phase shift on each antenna elements. This excitation matrix is shown on Figure 14.

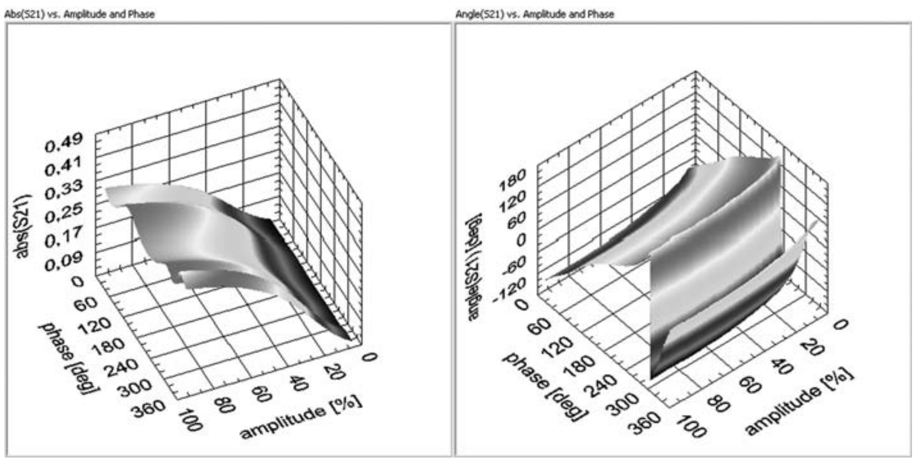

Fig. 11 2D calibration matrix of the 1 st. transmit channel

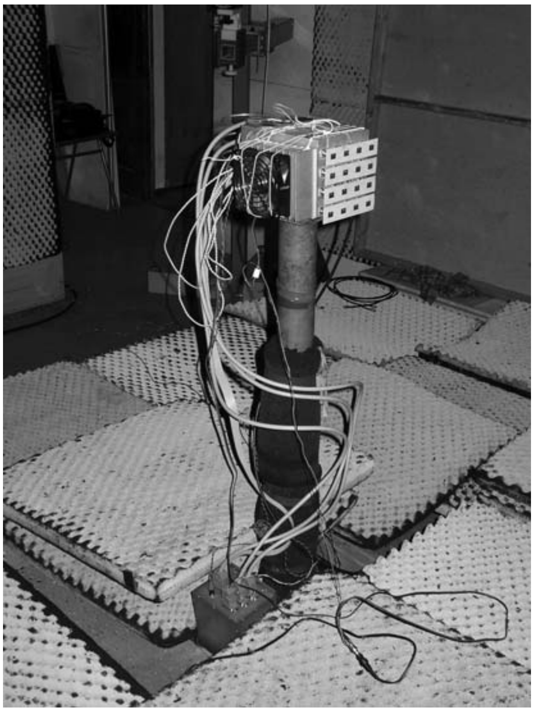

Fig. 12 Antenna pedestal for antenna measuring

Fig. 13 Receiver horn antenna

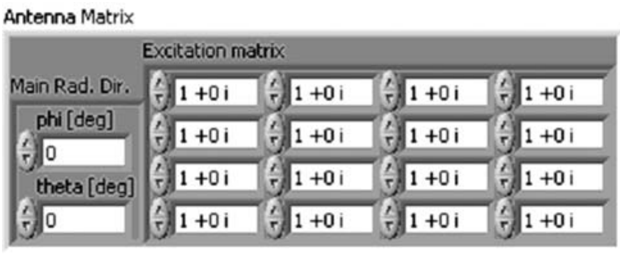

Fig. 14

The horizontal section of the 3D radiation pattern is on Figure 15 (polar diagram), and Figure 16.

The vertical section of the 3D radiation pattern is on Figure 17 (polar diagram), and Figure 18.

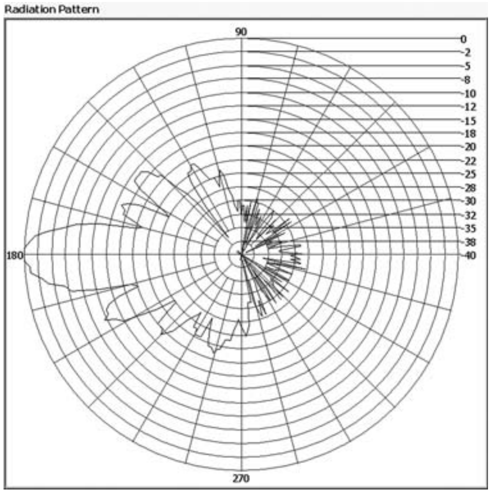

Fig. 15 Horizontal section

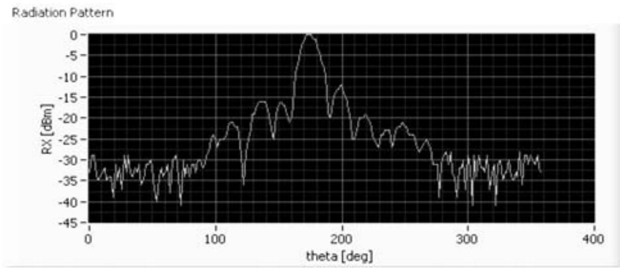

Fig. 16 Horizontal section

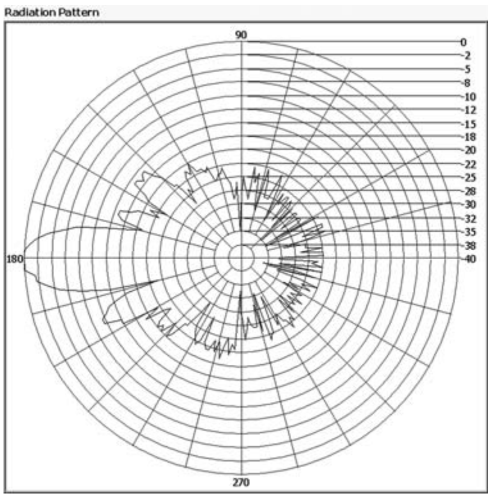

Fig. 17 Vertical section

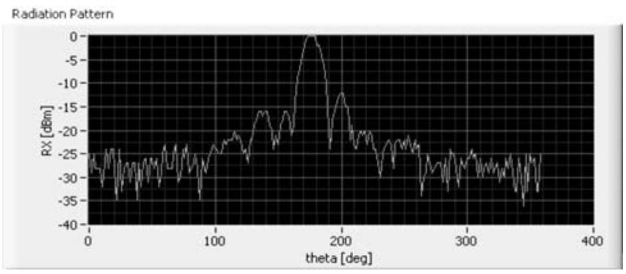

Fig. 18 Vertical section

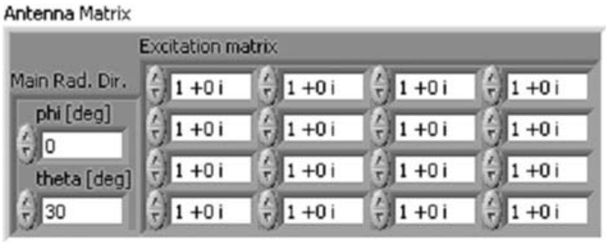

Fig. 19 The excitation matrix when the main radiation direction is 30 and 0 degrees

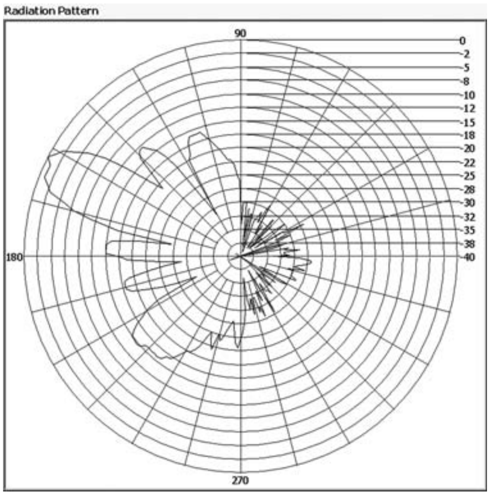

Fig. 20 Horizontal section

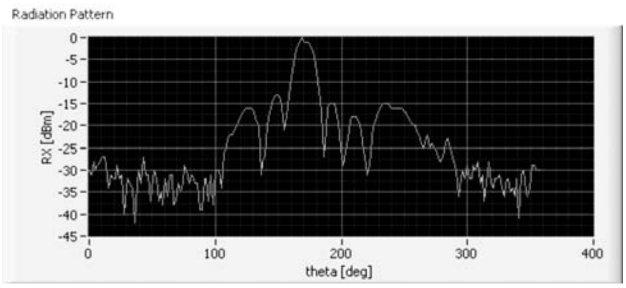

Fig. 21 Horizontal section

If we adjust the progressive phase shift on the antenna elements, the main radiation direction will tilt. In this case, the excitation matrix is on Figure 19, the horizontal section of the 3D radiation pattern is on Figures 20 and 21.

The 3D radiation pattern of the rectangular antenna array – where the main radiation direction is $\vartheta=0°$, $\varphi=0°$ with constant 2D amplitude distribution – is our newest measurement result, where ϑ runs from 0 to 360 degrees, and φ runs from 0 to 40 degrees – see Figure 22.

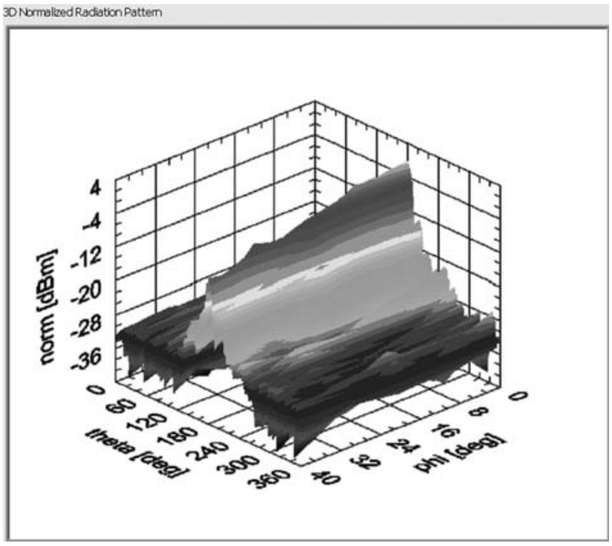

Fig. 22 3D radiation pattern

If we use an illumination function (e.g. raised cosine), we are able to form the main lobe width and the side lobe level – see Figures 23...25.

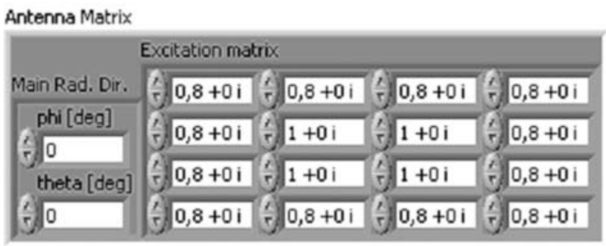

Fig. 23 Raised cosine illumination function in 2D

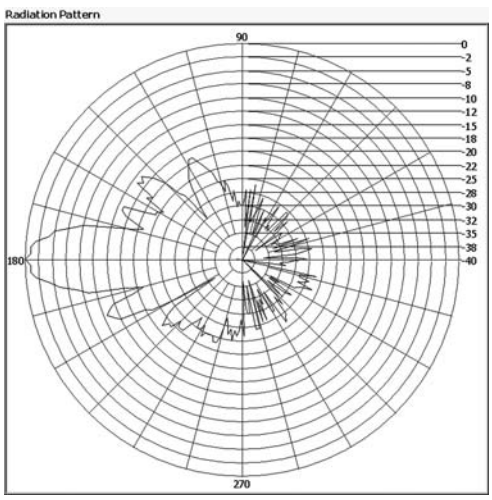

Fig. 24 Horizontal section

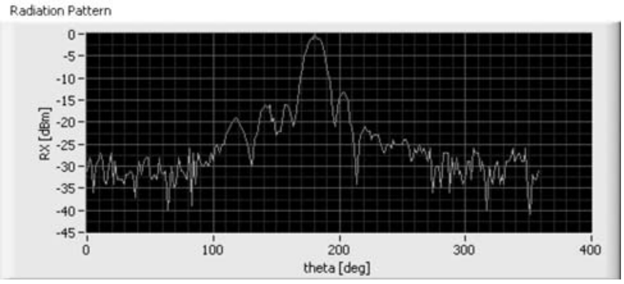

Fig. 25 Horizontal section

3 CONCLUSION

We have developed a 2D X-band digital beamformer rectangular antenna array and processed the automatized calibration to compensate the amplitude and phase errors on the RF routes.

We are going to make further antenna radiation pattern measurements and upgrade the controller software to be able to compute with the elementary antenna factor and the mutual impedance between the elementary antennas. The importance of these effects will increase if a low side lobe level illumination function is used.

The presented approach is a cost effective solution to make experimenting possible with digital beamforming applications, containing modern semiconductor devices either in RF or in digital parts.

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Digitalno oblikovanje dijagrama zračenja dvodimenzionalnog antenskog niza za pojas frekvencija X. Naša je namjera razviti mikrovalnu antenu čijim se dijagramom zračenja može upravljati elektronički. Dijagram zračenja običnih antena određen je Fourierovom transformacijom kompleksne funkcije pobude aperture antene. Taj je dijagram zračenja određen izvedbom antene i njegova izmjena nije moguća. Stoga se naš antenski sustav sastoji od više antenskih elemenata. Svi se antenski elementi pobuđuju odvojenim odašiljačima pa je moguće ugađati amplitude i faze pobudnih struja antenskih elemenata. Na taj način možemo upravljati dijagramom zračenja antenskog sustava. Upravljanje je izvedeno pomoću računala tako da je moguće vrlo brzo mijenjati dijagram zračenja.

Ključne riječi: DBF, DBAS, fazno upravljani antenski niz, inteligentna antena

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