their values are used in the antenna pattern synthesis for given excitation voltages $\mathbf{U}$.

C. Optimization criteria in adaptation process

The task for the adaptive algorithm in the smart antenna system is to find the optimum weights, which will minimize cost function defined. The signal to noise ratio has been taken into account as the optimization criteria which may be applied to any system where the receiver is capable of supplying the information on the quality of the received signal. According to the Monzingo and Miller, the signal to noise ratio at the array elements can be expressed as:

$$SNR = \frac{\mathbf{w^H}\,\mathbf{R_S}\,\mathbf{w}}{\mathbf{w^H}\,\mathbf{R_N}\,\mathbf{w}} \qquad (2)$$

where $\mathbf{w^H}$ - hermitian transpose, $\mathbf{R_S}$, $\mathbf{R_N}$ - signal and noise covariance matrices ($\mathbf{R_N}$ includes interference and internal array noise $\mathbf{R_N} = \mathbf{R_I} + \mathbf{R_N}$).

The covariance matrix for the signal can be obtained from radiation pattern equation $F(\theta) = f(\theta)\,\mathbf{R_S}\,\mathbf{w}$, where $f(\theta)$ represents single element characteristics. In the same manner, covariance matrix for the interference can be obtained by changing the angle θ_S to θ_I. From (2) the cost function fc has been defined as follows:

$$fc = \left(\frac{\mathbf{w^H}\,\mathbf{R_S}\,\mathbf{w}}{\mathbf{w^H}\,\mathbf{R_N}\,\mathbf{w}}\right)^{-1} \qquad (3)$$

In the process of adaptation the weights are supplied by the algorithm, and the covariance matrices are calculated for a given signal and interference directions of arrival.

III. Computer Simulations and Experiments

A. The influence of real antenna parameters on radiation pattern

The mutual impedances have been calculated for linear array consisting of 4 elements of $\lambda/4$, spaced by $\lambda/2$ over large conducting plane. Such a structure allowed easy realization of the array itself as well as the hardware feeding elements. The prototype antenna array was built from aluminium elements and the size of the plane was $4\lambda \times 5.5\lambda$. The radiators ware made of silver covered wires welded to the pins of the SMA connectors. The radiators were placed symmetrically along the longer side of the metal plate.

Measurements of the mutual couplings were performed with the use of the HP8712ET network analyzer working in the reflection coefficient measuring mode in the complex form. Fig. 2 depicts the comparison of radiation patterns of an ideal array and array for which calculated and measured mutual couplings were taken into account. Presented results have been obtained in

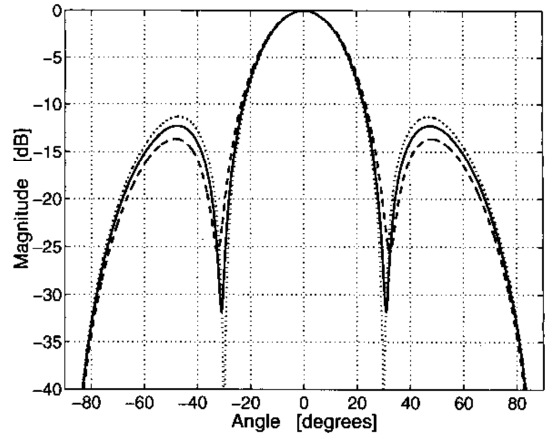

Fig. 2: Influence of mutual couplings on radiation pattern of a 4-element uniform linear array; solid line – pattern for measured mutual couplings, dashed line – pattern for calculated mutual couplings, dotted line – pattern of an ideal array

computer simulations run under MATLAB. Functions containing description of the model of the antenna and those enabling radiation pattern generation are used in the process of weight adaptation.

It can be seen, that mutual couplings of proposed antenna not only widen the mainlobe and cause shift in the positions of nulls in the resulting radiation pattern by few degrees but also limit the nulling ability to about -32dB.

This null displacement can be significant from the point of view of the process of adaptation do desired signal and interference. In a situation when the algorithm tunes the weight so that the received signal quality is highest, it is probable that in further processing of the angular position of the signals in given electromagnetic environment incompatibility with real situation will occur.

B. The adaptation process controlled by genetic algorithm

A simple structure of genetic algorithm was adopted and further developed to suit the optimization task. The investigation of genetic algorithm behavior in this particular task concerned estimation of its optimal parameters values, which is covered in [2].

Simulations of adaptation process of smart antenna shown in Fig. 1 were carried out for scenarios where only signal of interest is present and also when signal and interference of different angular spacing is present. In order to obtain stable results describing algorithm convergence, simulations of all parameter settings required were carried out in large numbers so that good statistical data have been collected. Since the genetic algorithm may be structured in several ways, these were examined to choose the most effective one. The best results were obtained for roulette wheel selection with uniform crossover, and the values of the crossover and mutation probabilities were 50% and 3% respectively.

In order to estimate the effectiveness of the genetic algorithm, it was compared with other methods like gradient algorithms, modified Powell algorithm and random search algorithm [2]. Due to the nature of this task which is a global search, gradient methods turned out to be ineffective. Although a large number of cost function executions required in the case of genetic algorithm contributes to large processing load, it proved to find better solution than other algorithms used. For a complex cost function definition including not only desired signal but also interference, convergence time for tested methods was closer. This confirmed more robust behavior of genetic algorithm for functions with more than one solution.

C. Parameters of the system

The structure of the smart antenna hardware is presented in Fig. 1. The design of the microwave circuits constituting the system was carried out with the assumptions that the system will be working at single point frequency of 1.2GHz and that the bandwidth will not be a prime concern in evaluating it's functionality. With regard to simplicity of construction and ease of manufacturing, nonsymmetrical microstrip line technique has been adapted. The design process was carried out with the use of circuit simulator software TOUCHSTONE and MWOffice. Designed modules were made on PCB drilling machine QuickCircuit and measurements were carried out with the use of HP8712ET network analyzer.

In order to obtain 360 degrees phase shift, the phase shifters were build on the base of a cascade of two 3dB hybrid couplers with reflection circuits realized on varactor diodes type MA46H202-1088. Inductances were realized as microstrip lines and the other components were SMD. The circuits were built on the GML 1000 laminate characterized with the following parameters: $h = 1.524$mm, $t = 0.035$mm, $\varepsilon_r = 3.05$. For the phase shifter characterized with the worst parameters, the reflection parameter s_{11} is within the range from -19.6dB to -61.5dB. For other circuits this parameter is not only better but occurs at different control voltage of the varactor diodes. The variation of the transmission parameter of the phase shifters is $s_{21} \leq 0.97$dB. With all four phase shifter circuits the achievable phase shift is greater than 360 degrees. The reason for differences between the parameters of those circuits is that they were made separately. The phase-to-control voltage characteristic is not linear, however it does not matter, as it can be easily corrected in the software when digitally synthesized.

The design of power combiners was based on the Wilkinson bridge. The parameters of the circuits were as follows: $s_{11} \leq -32$dB, $s_{22}, s_{33} \leq -28$dB, $s_{32} \leq -37$dB.

After all the circuits have been characterized with S parameters, they were connected into a system presented in Fig. 1. The results of measurements of the system parameters performed with reference to all possible phase shift settings are presented in Fig. 3 and 4. The measurements confirmed good reflection from all four ports of the network channels and also good

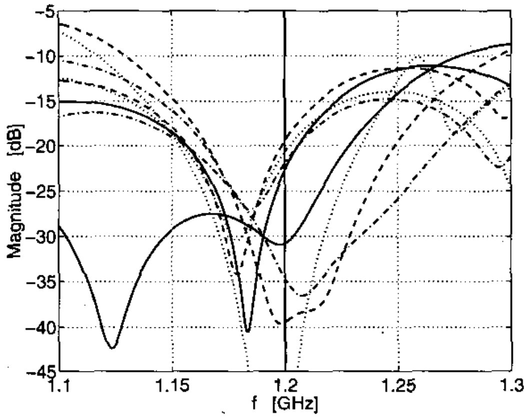

Fig. 3: S parameters of the complete system; min and max levels of reflection from all inputs: A (solid line), B (dashed line), C (dashdot line), D (dotted line)

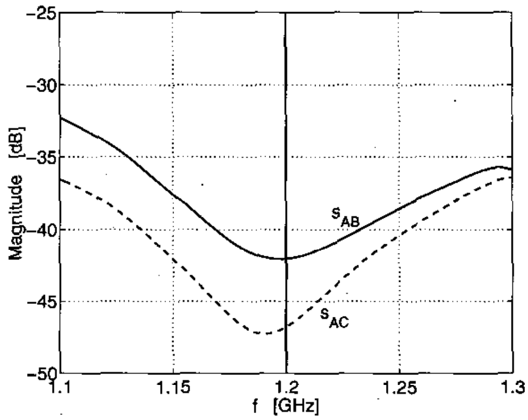

Fig. 4: S parameters of the complete system; maximum levels of isolation between the channels: A B (solid line), A C (dashed line)

isolation between them. Plots depicted in Fig 4 represent only the worst isolation of the channels, which is much better for other possible combinations. The levels of isolation change with the phase shifts only by 0.8dB. The first set-up of the system exhibited poor isolation between the channels, which also presented large dependence on the actual phase setting of the phase shifters. This was due to the fact that the boards of the microwave circuits were not shielded from external electromagnetic environment. Although putting screens on the boards resulted in small degradation of the stand alone circuit parameters, mainly the reflection losses, measurements of the complete system confirmed large improvement of the overall characteristics. All parameter values given in this paper apply to the modified hardware set-up.

Steering the phase delay in each channel of the smart antenna system was realized by means of I^2C standard transmission between the printer port of the PC computer and the digitally controlled potentiometers with additional circuitry on the other end of the line. The I^2C standard was chosen to facilitate communication setup, allowing to use as little hardware as possible outside the PC. The electronics needed was designed and built so that the PC is galvanicaly separated from the antenna and all the microwave devices.

D. *The radiation pattern of the smart antenna*

Figures 5 and 6 depict measured radiation characteristics of the experimental smart antenna setup for different signal and intereference directions. Radiation

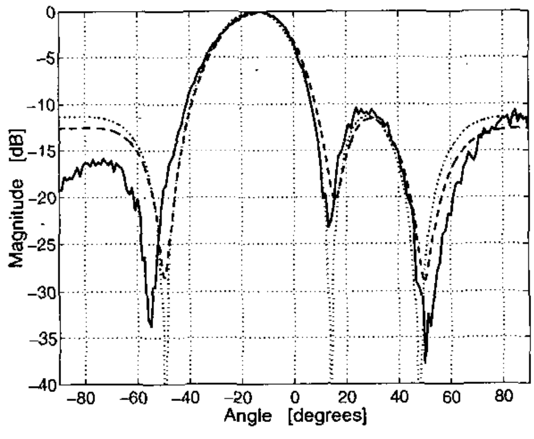

Fig. 5: Radiation pattern adapted to signal at $\theta_S = -15^o$; solid line – measurement of operating realized smart antenna, dashed line – simulation of a real array, doted line – simulation of an ideal array

pattern of an ideal antenna array is shown for comparison. An appropriate phase shift on each antenna

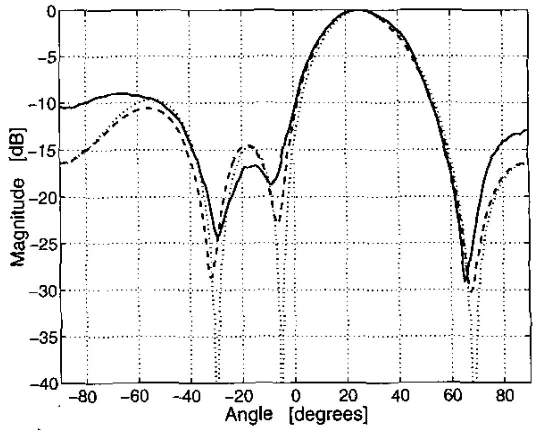

Fig. 6: Radiation pattern adapted to signal at $\theta_S = 25^0$ and interference at $\theta_I = -30^0$; solid line – measurement of operating realized smart antenna, dashed line – simulation of a real array, doted line – simulation of an ideal array

element was set through the computer program working in conjunction with the adaptive algorithm. Little deviations between ideal and measured characteristics that can be observed are caused mainly by the mutual couplings. Due to the fact that the antenna pattern measurements were carried out outdoor in low temperature conditions, which affected the electronics, some of the patterns experience larger shifts.

IV. Conclusion

Radiation characteristics of the prototype antenna were compared with those obtained in computer simulations for various scenarios of signal and interference. The system presented good ability to place nulls in the interference direction at the level ≤ -24dB in the worst electromagnetic conditions. Analysis of the array patterns confirmed that for certain sets of signal's directions mutual couplings have more limiting influence on the null placement.

Performance of the system depends on the assumptions concerning antenna model and characteristics of the microwave circuits. Measurements of these modules enabled verification of assumptions concerning their theoretical parameters and analysis of the influence of those parameters on resulting radiation pattern of the experimental smart antenna setup.

References

[1] M. Chryssomallis. "Smart antennas". *IEEE Antennas and Propagation Magazine*, Vol. 42(No. 3), June 2000.

[2] M. Piasecki, Y. Yashchyshyn. "Improved model of adaptive antenna controlled by genetic angorithm". In *Proc. of the European Microwave Week 2001, Wireless Technologies 2001*, pages 97–100, Excel, London, Great Britain, 24 - 28th September 2001.