# Linear Pattern Correction in a Small Microstrip Antenna Array

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***Abstract*—Mutual coupling effects on the radiation patterns of small microstrip antenna arrays suitable for mobile communications applications are studied. The correction of experimental antenna patterns by changing array feed coefficients is examined for 5 GHz linear microstrip arrays with different element spacings. The use of either the element radiation patterns or the scattering parameters to determine the correction matrix is studied. It is shown that the correction can decrease considerably the difference between the real and desired array patterns. The validity of the correction is proven also over a frequency band of 5.0–5.4 GHz using fixed corrected input vectors over the whole frequency band.**

***Index Terms*—Antenna array, microstrip array, mutual coupling, pattern correction.**

## I. Introduction

Mutual coupling between antenna elements is problematic in antenna arrays as it may distort the element patterns. In small arrays the resulting element patterns are different from each other and thus the resulting array pattern differs sometimes significantly from the desired one. Another problem resulting from mutual coupling is increased reflected power to antenna feed system due to poor impedance matching. Mutual coupling leads also to performance degradation in radio systems. It decreases the signal to interference plus noise ratio (SINR) and increases the response time of an adaptive array [1].

In small arrays pattern distortion due to mutual coupling can be partially corrected by tuning the feed voltages. Linear correction is performed by multiplying the desired input vector with a correction matrix. The linear matrix correction is simpler than input coefficient iteration and can therefore be used in real-time adaptive algorithms. Simple matrix methods were developed and used for arrays of rectangular waveguides in [2] to compensate the mutual coupling effects on array patterns using a correction matrix derived from either measured element patterns or scattering matrix. The scattering matrix method was applied to slotted waveguide array in [3] and the pattern method for planar printed dipole array in [4]. A linear least square error (LSE) feed voltage correction method was studied experimentally for square patch element arrays in [5]. From the practical array calibration point of view the measurement of the scattering matrix of a small array is clearly easier and requires less expensive facilities than the measurement of element patterns.

The linear array is a frequently used type of antenna array to produce different beams in the horizontal plane for cellular mobile communications. We examine a small linear microstrip antenna array as a potential candidate for an adaptive antenna in mobile communications and thus the correction of nonidealities of a microstrip array is of interest. First, an element pattern based correction method (called LSE method in this paper) is tested at single frequency with different types of desired patterns. The correction results are compared with those provided by the scattering matrix based method. We show also, how the LSE correction method works over a frequency band for the practical example of one certain correction matrix. The correlation between corrected and desired patterns is used as the validity criterion of the correction methods.

This paper is organized as follows: Section II contains the basic theory of pattern correction. In Section III the measured antenna elements and arrays are described as also the measurements. Section IV concentrates on array pattern correction: first on correction at a single frequency with the LSE method and for comparison also with other correction methods. The section ends with a correction study over a frequency band and Section V contains the conclusion.

## II. Theory

Antenna array pattern $\vec{\boldsymbol{\Psi}}$ is a linear combination of antenna element patterns in the array and can be presented in vector form as

$$\vec{\boldsymbol{\Psi}} = \vec{\mathbf{a}}^{\mathrm{T}} \cdot \mathbf{F} \tag{1}$$

where $\vec{\mathbf{a}}^{\mathrm{T}}$ is a feeding vector containing complex weighting coefficients for $N$ antenna elements. Pattern matrix $\mathbf{F}$ is a complex value $N \times M$ matrix of $N$ element patterns with $M$ observation directions. It contains amplitudes and phases for each element pattern in different directions. In the general case all directions and also full polarization information are included.

Using correction matrix $\mathbf{K}$ with dimensions $N \times N$ we can produce new *rep*aired element patterns $\mathbf{F}_{\mathrm{rep}}$ from *meas*ured patterns $\mathbf{F}_{\mathrm{meas}}$

$$\mathbf{F}_{\mathrm{rep}} = \mathbf{K} \cdot \mathbf{F}_{\mathrm{meas}}. \tag{2}$$

Here, the problem for finding the correction matrix $\mathbf{K}$ is solved using Moore–Penrose pseudoinverse defined as $pinv(\mathbf{F}) = \mathbf{F}^{\mathrm{H}}(\mathbf{F}\mathbf{F}^{\mathrm{H}})^{-1}$ [5], [6]. The use of matrix pseudoinverse gives an LSE solution including phase information and is

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used in different array problems [7]–[10]. The formula for the correction matrix $\mathbf{K}$ is then

$$\mathbf{K} = \mathbf{F}_{\mathrm{des}} \cdot pinv(\mathbf{F}_{\mathrm{meas}}) \tag{3}$$

where matrix $\mathbf{F}_{\mathrm{des}}$ contains the *des*ired element patterns. The corrected (*rep*aired) array pattern $\vec{\mathbf{\Psi}}_{\mathrm{rep}}$ is now

$$\vec{\mathbf{\Psi}}_{\mathrm{rep}} = \vec{\mathbf{a}}_{\mathrm{des}}^{T}\mathbf{K}\mathbf{F}_{\mathrm{meas}} = \vec{\mathbf{a}}_{\mathrm{des}}^{T}\mathbf{F}_{\mathrm{rep}} = \vec{\mathbf{a}}_{\mathrm{rep}}^{T}\mathbf{F}_{\mathrm{meas}}. \tag{4}$$

The different presentations for corrected array patterns in this formula are identical. However, the use of them can differ occasionally, if only the necessary information is stored. When fixed array patterns with constant feeding vectors are used, only the corrected feeding coefficients $\vec{\mathbf{a}}_{\mathrm{rep}}$ can be stored and used. In the case, where the input coefficients alter, the correction matrix $\mathbf{K}$ must be stored. In practice in mobile communications, when the array in mobile base station is receiving, the correction can be done electronically or through calculations. If the array is transmitting the corrected RF weights should be used. To solve the matching problem and correction at the same time is difficult. The matching problem for arrays is nontrivial in the general case [11].

In general, the desired element patterns for an array can be different. The isotropic antenna element patterns are usually used as the desired element patterns in antenna array synthesis and in adaptive algorithms and then in principle an array with such an element pattern is needed [2], [4], [12]. The information to be stored is minimal for an array of isotropic elements, which saves resources.

Often in the stationary case we are interested in optimizing the array amplitude pattern $|\vec{\mathbf{\Psi}}(\theta)|$, without considering the phase, but in linear correction we get array pattern $\vec{\mathbf{\Psi}}(\theta)$ with phase information. This means that the best solution for the wanted array amplitude pattern without phase information is not completely reached with the linear matrix method and thus some further iteration is required. The array pattern phases are usually arbitrary for a stationary array, but not for an adaptive one. In the case of alternating feeding coefficients the use of a correction matrix is relatively simple compared with iteration and thus potentially usable with all adaptive algorithms including the case of amplitude-only criterion for the array pattern.

The correction method based on scattering matrix discussed in [2] does not use desired element patterns. This method is based on the assumed direct dependency between aperture voltages or fields and the scattering matrix and can be used in arrays of simple antenna elements. In this case the correction matrix should be

$$\mathbf{K} = (\mathbf{I} + \mathbf{S})^{-1} \tag{5}$$

where $\mathbf{I}$ is a unity matrix and $\mathbf{S}$ is the scattering matrix. This method is used for a small linear array in [2] and [3]. The advantage of this method is, that it needs only a measured or modeled scattering matrix to correct adaptive antenna input voltages. It can be compared with the LSE method, which gives always the best result in the sense of squared error, but requires desired and measured array patterns. Basically, the scattering matrix method can give only diagonally symmetric correction matrix due to reciprocity of the scattering matrix.

Another correction method using measured and desired element patterns presented in [2] is the "Fourier transform method." It is similar with the weighted integration of patterns presented in [4]. Different direction-dependent weights and integration limits can be used. These other methods that use pattern information are presented here only briefly, because for the used LSE criterion pseudoinverse is the optimal method.

The validity of the correction is assessed in this paper by comparing the corrected array pattern with the desired one. This complicates the comparison of the validity of the scattering matrix method with other methods, because in this kind of comparison the scattering matrix method is more sensitive to radiation pattern measurement errors than those based on pattern information. The methods that correct measured array patterns to desired ones can trivially correct also pattern measurement errors. Of course in this case the defined correction is not purely the true array correction.

We have used correlation $r$ in the form of normalized complex scalar/inner product as the validity criterion for the pattern correction

$$r = \frac{|\vec{\mathbf{\Psi}}_{\mathrm{rep}} \cdot \vec{\mathbf{\Psi}}_{\mathrm{des}}|}{|\vec{\mathbf{\Psi}}_{\mathrm{rep}}||\vec{\mathbf{\Psi}}_{\mathrm{des}}|}. \tag{6}$$

This vector project form is simpler than the usual form for correlation with extracted means. The mean values are forced to zero. This is done because there should not be any vector added to change the complex ratio of the elements in different pattern vectors in the comparison. This is also in agreement with the used LSE method, where the compared pattern vector can be divided into correlated parallel and uncorrelated orthogonal component. In the used complex form this relation is called as coherence between two signal vectors [13] and is usable in coupling study of arrays [14]. An alternative for the correlation criterion is the acorrelation criterion used in [10]. The correlations before and after correction are so close to one, that for convenience also another parameter; correction $CR$ is used here. It is defined as

$$CR = \frac{1 - r_0}{1 - r_c} \tag{7}$$

where $r_0$ and $r_c$ are the correlations between the desired array pattern and the real pattern before and after the correction, respectively.

## III. Measurements

### A. Measured Antennas and Generated Arrays

Five arrays of six rectangular microstrip patches were examined. They were prepared on Rogers RT/duroid 6002 substrate with permittivity $\varepsilon_r = 2.94$ and substrate thickness $h = 1.52$ mm. The array layout is shown in Fig. 1. The matching of the microstrip element is reached by adjusting the location of the coaxial feed point for a single element and used for all patches in arrays. The designed resonant frequency for the elements was 5.3 GHz, the realized ones are somewhat lower, typically from 5.2 to 5.3 GHz, and they differ from each other in the array.

Four of the measured antenna arrays have the same substrate plate dimensions ($l = 197\ \mathrm{mm} \approx 3.4\lambda$, $w = 56\ \mathrm{mm} \approx 1.0\lambda$).

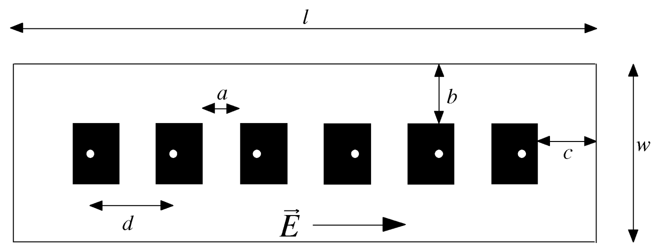


Fig. 1. Microstrip antenna array layout with element spacing $d$. The backside of the substrate plate is fully metallized with copper. The feed probe is zoomed to be clearly visible.

With these substrate plate dimensions the element spacing $d$ is $0.3\lambda$ for one array and $0.5\lambda$ for the others. In these cases the distance $c$ from the plate edges to the first or last element varies from about $0.3\lambda$ to about $0.8\lambda$. The respective distance $b$ in the perpendicular direction is about $0.3\lambda$ and for one array with vertical polarization (elements rotated 90° compared to those on Fig. 1) $b \approx 0.4\lambda$. The array with element spacing $d = 0.93\lambda$ was prepared on a larger substrate plate with $c \approx 1.6\lambda$ and $b \approx 0.7\lambda$. The patch elements in all arrays have the same dimensions (15.4 mm $\times$ 20.2 mm). The distance $a$ between elements varies from 0.003 $\lambda$ to 0.65 $\lambda$ (2 to 37 mm) with element spacing $d$ from $0.3\lambda$ to $0.93\lambda$.

The orientation of the patch antenna elements in the examined arrays is with one exception that presented in Fig. 1, where also the direction of the measured electric field $\vec{\mathbf{E}}$ is shown. In one array with element spacing $d = 0.5\lambda$ the direction of the patch elements in the array defining the polarization is rotated 90° compared to that in Fig. 1. In the case of Fig. 1 the input ports are placed symmetrically to the array center to have in principle a symmetric array so that the possible pattern asymmetry indicates inaccuracies in the array realization. Three of the tested arrays have such symmetric configuration and in two arrays the orientation of all elements is equal. The input coefficients presented in this paper for the symmetric arrays are the weight coefficients relative to the antisymmetric input vector $[1\ 1\ 1\ -1\ -1\ -1]$, so that the feeding vectors used later in this work are the same for the symmetric and usual periodic arrays. The measured scattering matrices are processed if needed in the same manner so that the signs of the upper right and lower left blocks are changed. This input and scattering matrix presentation is equal to having in the measurements of symmetric arrays a 180° phase shifter at the right hand element ports.

To compare the substrate edge and the mutual coupling effects in the arrays also single elements were prepared on a substrate plate with dimensions 197 mm $\times$ 56 mm. To examine the effect of the size of the ground plane an additional large metallic backplate was used to maximize the distance from patches to ground plane edges. The dimensions of the backplate ($L = 900\ \mathrm{mm} \approx 16\lambda$, $W = 680\ \mathrm{mm} \approx 12\lambda$) were clearly larger than the dimensions of the substrate plate. A single element with small substrate plate (38 mm $\times$ 42 mm) was used to obtain model patterns and information on substrate edge effect.

Measured patterns and theoretical patterns have been used as desired element patterns in the correction. Measured desired patterns were the single microstrip element pattern or the mean of centered patterns of all elements in the array or optionally the mean pattern of only the central elements. RF absorbers were also used to cover other antenna elements and especially the edges of the array to have symmetric desired element patterns with smooth substrate edge effect. The theoretical desired pattern was calculated for microstrip element using the formulas based on a two-slot model [15].

### B. Patterns and Scattering Parameters

Antenna array element patterns were measured at frequencies from 5.0 to 5.4 GHz in an anechoic chamber. A horn antenna was used as the measurement antenna. The antenna pattern and scattering parameter measurements were carried out using a vector network analyzer. The scattering matrix was measured at frequencies from 3.0 GHz to 6.0 GHz for the correction method presented in [2].

In the experiments the copolarized field pattern was measured individually for each element in the horizontal plane. Measured patterns have 360 measurement points with 1° spacing. Each array element pattern was measured so that the other elements were terminated with matched loads. This kind of pattern is so-called active pattern, which the antenna element has, when placed in the array and is affected by mutual coupling and other near field effects.

The measured antenna element patterns are somewhat degraded due to nonidealities. In addition to the mutual coupling the substrate edge diffraction effect takes place, because the largest dimensions of the substrate plate are only a couple of wavelengths. Patterns of the elements near to edges become nonsymmetric, as can be expected for a small array [2], [4], [5]. The experiments with single microstrip antennas on the substrate plate with the same size as that of the array show, that the substrate edge effect (diffraction) and mutual coupling effects are of about the same order. In addition to amplitude oscillations in element patterns also the phases oscillate as noticed also in [16] for printed dipoles. When the microstrip antenna array was placed on a large metallic backplate, the edge element patterns became more symmetric, but very rippled due to diffraction. For a single element on a small substrate plate the element pattern is very smooth compared to those in arrays.

The backlobe level defines the practical goal for the sidelobe level for the real microstrip array pattern synthesis. This level is about $-30 \ldots -20$ dB for the examined arrays, when measured without the additional large metallic backplate. According to [17] the back radiation and sidelobe level depend strongly on each other in a microstrip array. The symmetrized arrays prepared locating the element feed points symmetrically to each other do not have exact symmetry between their element patterns, which indicates preparation inaccuracies. The measurement uncertainty (standard deviation) was about 0.4 dB for the pattern amplitude and about 5 degrees for the phase. These measurement inaccuracies are caused mostly by the wall reflections in the anechoic chamber.

The increase of mutual coupling with decreasing element spacing is pronounced. Also the resonant bandwidth broadens somewhat and the matching at the resonant frequency becomes worse due to mutual coupling. Antenna elements in an array have slightly different resonant frequencies due to mutual coupling and other nonidealities. For the manufactured antenna

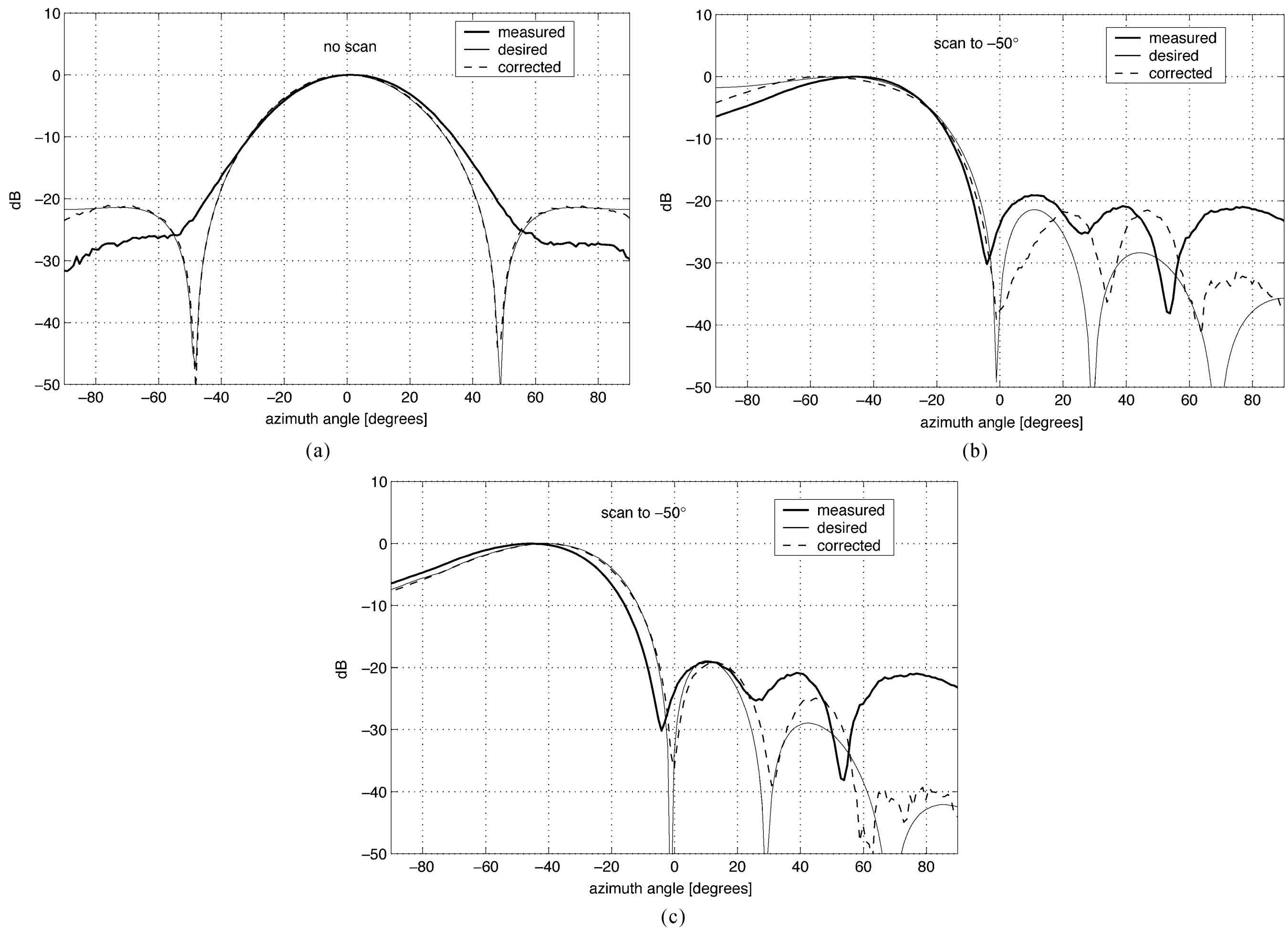


Fig. 2. Amplitude comparison of measured, desired and corrected array patterns. Beam is generated with input vector $\vec{a} = [2\ 4\ 5\ 5\ 4\ 2]$. (a) beam in forward direction. In (b) and (c) the beam is scanned to angle $-50^\circ$. In (a) and (b) the six-element microstrip array pattern is corrected using isotropic elements as model elements. In (c) the single microstrip antenna pattern is used as desired model pattern. The measured patterns are defined at 5.2 GHz. Element spacing is $0.3\lambda$ at 5.3 GHz. All the array patterns are scaled to have maximum of 0 dB.

array the typical levels of the reflection coefficient $|S_{ii}|$ at resonant frequency are about $-15$, $-27$, and $-30$ dB and coupling coefficients between neighboring elements $(|S_{12}|, |S_{23} \ldots)$ about $-9$, $-20$, and $-22$ dB for element spacings of $0.3\lambda$, $0.5\lambda$, and $0.9\lambda$, respectively. These values are in agreement with those presented in references [18]–[20]. The measurement uncertainty (standard deviation) for the absolute values of the scattering parameters was characterized to be about 0.2 dB (5%) and for the phase about 3°. The eigenvalue analysis of the scattering matrix for the array with close spacing $d = 0.3\ \lambda$ shows, that the total reflected power from the array to the feed system can be as high as 90% of the array input power. The corresponding input vector is, however, not connected to any specific radiation beam scan, for which the beam could disappear indicating the scan blindness discussed in [21].

## IV. Pattern Correction Results

### *A. Correction at Single Frequency With LSE Method*

Examples of array pattern distortion and linear correction are shown in Fig. 2. The frequency is 5.2 GHz, array element spacing $0.3\lambda$ and the normalized input vector [2 4 5 5 4 2]. This is an example of an input vector giving in the forward direction a compact pattern with low sidelobes. In Fig. 2(a) the measured, desired and corrected array patterns are presented when the beam points to forward direction $(\phi_0 = 0^\circ)$. The most pronounced effect of nonidealities is the disappearance of nulls. The correction is realized using only the forward parts $(\phi = -90^\circ \ \ldots \ +90^\circ)$ of measured and desired patterns in calculations. The corrected feeding coefficients are $[(2.1\underline{/\,3^\circ})\ \ (4.7\underline{/-7^\circ})\ \ (4.3\underline{/-5^\circ})\ \ (4.6\underline{/-3^\circ})\ \ (4.5\underline{/-2^\circ})\ \ (2.2\underline{/14^\circ})]$ instead of [2 4 5 5 4 2], where the scaling of the corrected input vector is done to match the complex mean to that of the desired input vector. The standard deviation for the required phase changes in this correction case is about 8° and for the relative amplitude changes about 0.9 dB (20%), which are significantly larger than the measurement uncertainties. In this case the correlation between desired and corrected array patterns is 0.9998, when the value of correlation before correction was 0.9897. The correction factor is $CR = 65$. This result shows that the nulls and sidelobe levels can be corrected very well. In the case of Fig. 2(a) the uncorrected array pattern is smooth with lower sidelobes and could be used also without correction.

In Fig. 2(b) the main beam is scanned to $\phi_0 = -50^\circ$ and the correction is not as good as above. The correction accuracy gets poorer in the main beam region and thus the LSE criterion allows also the positions of nulls and sidelobe levels to vary more. In this case the corrected input vector without the progressive phase factor of the scan is $[(2.4\angle 47^\circ)\quad(0.7\angle -41^\circ)\quad(6.9\angle -44^\circ)\quad(8.0\angle -3^\circ)\quad(4.4\angle 26^\circ)\quad(1.1\angle 15^\circ)]$ and the correlations before and after correction are 0.979 and 0.995, respectively. The correction factor is only $CR = 4.7$. The correction matrix is the same in both cases $\phi_0 = 0^\circ$ and $\phi_0 = -50^\circ$ with different scan angles. When the desired array element patterns are generated with the single microstrip element pattern having similar radiation level at the endfire region as the array elements, the fitting in beam region is better within scan and this allows more accurate correction of sidelobes and nulls as is seen in Fig. 2(c). In this case the correction factor is $CR = 47$. To have better sidelobe and null correction, when isotropic desired patterns are used in the case of scan, the correction matrix can also be calculated using patterns only in a smaller region, e.g. $\phi = -60^\circ \ldots +60^\circ$. When isotropic antenna element patterns have been used as desired patterns, the correlations have been calculated only in the forward direction of patterns. More detailed information on the results for desired array pattern with isotropic element patterns in different cases of element spacing is given in Section IV-C, where the correction is generalized over a frequency band.

Generally, the typical array pattern correlation is before correction about 0.97–0.99 and after correction about 0.98–1.00. The matrix correction repairs the patterns of different elements in the array independently. For individual array elements in different arrays the correlations with desired element patterns before and after correction vary significantly from 0.90 to 1.00. Significant differences were not noticed between resulting array pattern correlations when using different desired element patterns for beams directed forward. For the array with a large substrate plate with $0.93\lambda$ element distance the array pattern correlations before and after correction were only 0.90–0.94. Also, with additional large metallic backplate the patterns become rippled.

### B. Comparison of Different Pattern Correction Methods

Two different pattern correction methods were compared in detail: The LSE method using pseudoinverse and the use of measured scattering matrix. With the LSE matching criterion the pseudoinverse is always the optimal method and should give the best results. In Fig. 3 we see an example of pattern correction with these two methods for an array with element distance $d = 0.5\lambda$. The desired element patterns are calculated with the two-slot model for patch antennas [15]. Also in these corrected array patterns we can see differences in null depths and locations as well as in side lobe levels. The correction results using these different methods are compared in Table I for all examined arrays at two frequencies, 5.2 and 5.3 GHz. The iterated scattering matrix (as described in this section) has been used to control the effect of reference plane adjustment. The results show that the presented correction methods can improve clearly the correlation between the desired and real array patterns. It is also seen

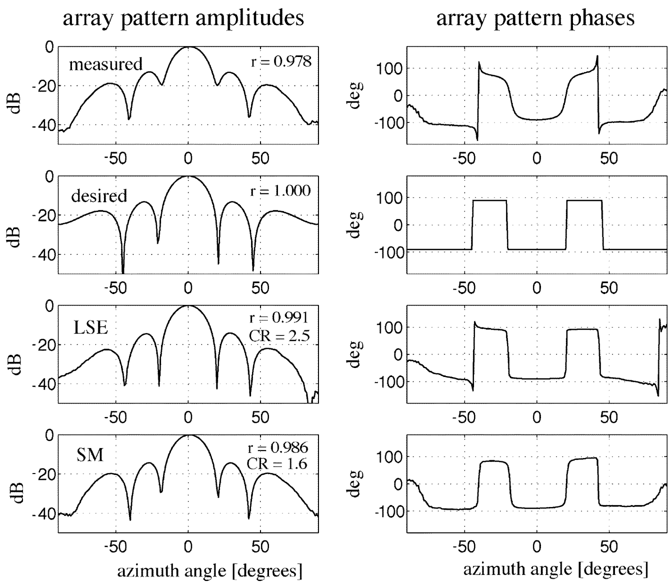


Fig. 3. Comparison of LSE correction method using patterns and the correction method using scattering matrix. The array element spacing is $0.48\lambda$, the elements are vertically stacked and the array ports are symmetrized (see Fig. 1). Input vector $\vec{\mathbf{a}} = [1\ 1\ 1\ 1\ 1\ 1]$, and, $f$ is 5.2 GHz. On the left side are the scaled array amplitude patterns and on the right side the corresponding phase patterns. From up to down are the measured array pattern, desired array pattern and corrected array patterns, corrected with LSE method (LSE) and corrected using scattering matrix (SM). The correlation $r$ between the array pattern and the desired array pattern is given. For corrected patterns the correction factor $(CR)$ is also given. The calculated lines are sketched between pattern points with direction angles of the pattern measurements.

very clearly, that the correction result becomes worse when the element spacing and/or substrate plate dimensions increase. The antenna symmetrizing procedure (see Section III-A) seems not to have any advantages.

The reference plane for scattering matrix measurements is usually not at the antenna aperture as necessary for the scattering matrix method of [2]. In this paper, the initial reference plane was chosen in the calibration to be at the lower end of the feed probe of an element. The final scattering matrix reference point is chosen to give for $S_{ii}$ the frequency dependency close to the ideal response of a parallel resonant circuit, which is known to be a good approximation of the input impedance characteristics of a patch close to the resonance [22], [23]. The shifting of the reference plane is set equal for all elements in different arrays. This reference point is about 45° toward the antenna element from the lower end of the antenna feed probe. The reason for this phase shift is mainly the inductance of the feed probe [24], [25]. Its calculated value is about 0.7 nH. In this work the frequency dependent correction matrix is $(\mathbf{I}+\mathbf{S})^{-1}$ for the antenna with parallel resonant equivalent circuit. For an antenna representing a series resonant circuit the position of the impedance circle is opposite to that of a parallel resonant circuit on the Smith diagram and the corresponding correction matrix would be $(\mathbf{I}-\mathbf{S})^{-1}$ (see [1], [11], and [26]).

Iteration of the scattering matrix was used to control the effect of the scattering matrix calibration on the correction. The general reference phases of the diagonal and nondiagonal elements of the scattering matrix were tuned independently from each other and for each array. With this manipulation one can

TABLE I
COMPARISON OF DIFFERENT CORRECTION METHODS AT 5.2 AND 5.3 GHz FOR ARRAYS WITH DIFFERENT ELEMENT SPACINGS. RESULTING CORRELATIONS WITH MODEL ARRAY PATTERN, WHICH IS GENERATED FROM THE PATTERN OF A THEORETICAL SINGLE MICROSTRIP ANTENNA ON INFINITE BACKGROUND PLATE WITH INPUT VECTOR $\vec{a} = [1\ 1\ 1\ 1\ 1\ 1]$

| Array properties | | Correlation between desired microstrip array pattern from literature [15] and measured array pattern at 5.2 GHz and 5.3 GHz. | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Measured | | Corrected with | | | | | |
| | | | | LSE | | Scattering matrix | | Iterated scattering matrix | |
| $d/\lambda$ | others | 5.2 GHz | 5.3 GHz | 5.2 GHz | 5.2 GHz | 5.2 GHz | 5.3 GHz | 5.2 GHz | 5.3 GHz |
| 0.30 | 1B), 2A) | 0.9895 | 0.9833 | 0.9996 | 0.9996 | 0.9943 | 0.9945 | 0.9950 | 0.9951 |
| 0.48 | 1B), 2A) | 0.9780 | 0.9762 | 0.9913 | 0.9891 | 0.9859 | 0.9829 | 0.9874 | 0.9850 |
| 0.48 | 1A), 2A) | 0.9883 | 0.9870 | 0.9921 | 0.9930 | 0.9874 | 0.9876 | 0.9880 | 0.9880 |
| 0.50 | 1A), 2B) | 0.9923 | 0.9922 | 0.9994 | 0.9994 | 0.9943 | 0.9947 | 0.9947 | 0.9948 |
| 0.93 | 1B), 2A), 3) | 0.9370 | 0.9258 | 0.9498 | 0.9356 | 0.9422 | 0.9287 | 0.9463 | 0.9340 |

1A) usual periodical array, 1B) antenna array with symmetrized input ports
2A) vertically stacked elements, 2B) horizontally stacked elements
3) the substrate plate is larger than for other arrays

find for each array a scattering matrix with higher correction level than when the scattering matrix is used with the same constant phase shift for all arrays. The deviation of the array-dependent iterated phases from the general reference phases are 20° for the diagonal and 35° for the nondiagonal parameters of the scattering matrix. In the iteration the region of maximum correlation is for all arrays flat and smooth, which means that exact parametric modeling requires significantly higher measurement accuracy than reached in this work. In the future more accurate correction results could be reached using a more detailed model such as the dual-slot model for microstrip antennas. In the case of very strong coupling with element spacing $0.3\lambda$ the iteration shows, that there could in some cases be stability problems in the scattering matrix based correction. There is a deep and smooth correlation minimum region with widths of about 50° and 150° in the plane of the two iterated phases of the scattering matrix, but there are also some deep and very sharp (region $< 1°$) correlation minima. These might be caused by scattering matrix eigenvalues, whose moduli are near to unity, leading to dividing by almost zero. The examined case with $d = 0.3\lambda$ is safe, as the distance between the used reference point and the nearest sharp minimum is more than 60° in the project direction of matrix diagonal element phase shift.

There are several facts that are against the use of the scattering matrix correction method of [2] in the case of a microstrip array. First, the microstrip antenna has a nonuniform aperture field, which cannot be expressed as a certain aperture voltage. The aperture actually consists of two separated radiating edges [27]. Further, the model in [2] ignores also the scattering by neighboring elements [28] and does not either take into account the ground plane edge diffraction effect (see [5], [17], [29], [30]). One additional problem in evaluating the feasibility of the scattering matrix method for a microstrip array is that it does not have any well-defined desired pattern for small arrays.

Other methods for pattern correction using only pattern information were also tested. The integral method called the "Fourier transform method" in [2] gives nearly the same correction as LSE method when element spacing is close to $\lambda/2$, but the correction is lost for other element spacings. The integral method defined in [4] gives with some element spacings better results than the "Fourier transform method," but is not better in general. To use the integral methods the orthogonal base of patterns is sufficient [2], [4], [12]. For wanted element pattern vectors it can be created for each spacing simply by using the Gram-Schmidt orthogonalization procedure.

### C. *Results of Correction Over Frequency Band Using Only One Correction Matrix*

The validity of array pattern correction over a frequency band with a fixed correction matrix and feeding vector was evaluated for all examined arrays more accurately. In this case we have used the LSE correction matrix calculated for the center frequency of 5.2 GHz and used it over the entire frequency band from 5.0–5.4 GHz. This band is somewhat broader than the band of HIPERLAN standard placed at 5.150–5.350 GHz [31]. Two different feeding vectors have been used, namely [1 1 1 1 1 1] and [2 4 5 5 4 2]. Examples of correction for symmetrized arrays with two element spacings ($d = 0.3\lambda$ and $d = 0.5\lambda$) are shown in Fig. 4. As desired array element patterns we have used here the patterns of isotropic elements at 5.2 GHz. The results are presented as correlation between the corrected and desired array patterns.

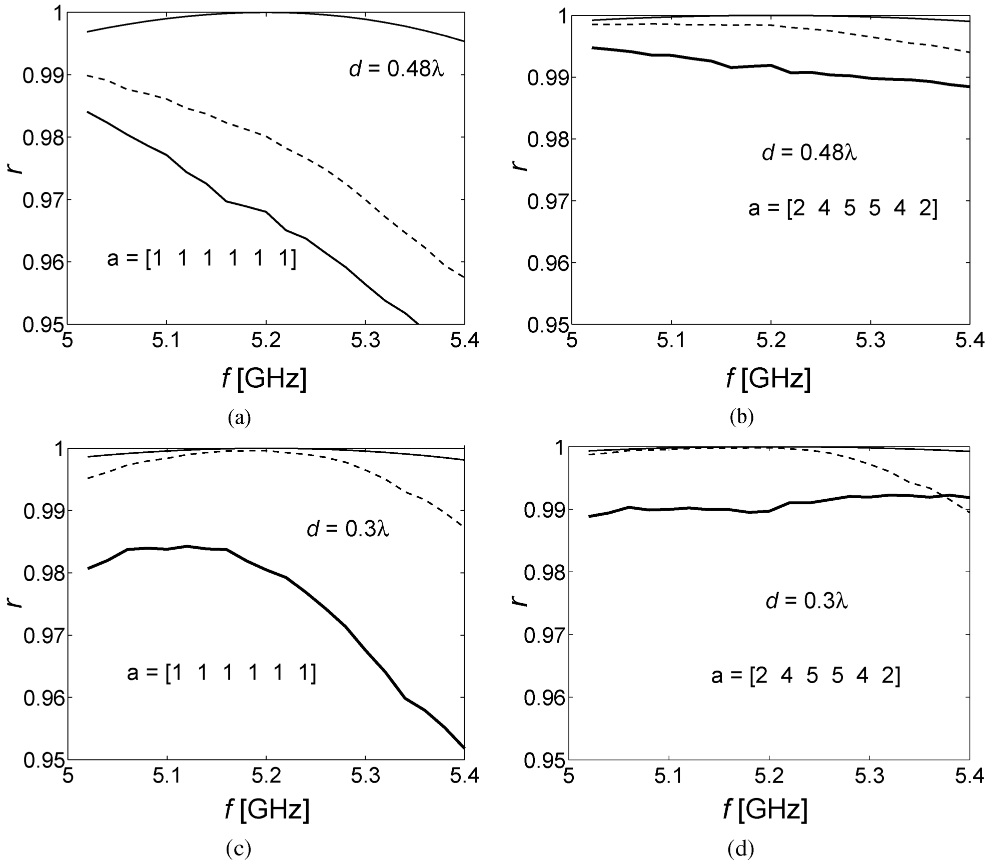


Fig. 4. The results for array pattern correction over a frequency band given as correlation $r$ between measured and desired array patterns (thick solid line), or between corrected and desired array pattern (dashed line). The desired array pattern is the array pattern of isotropic elements at 5.2 GHz. The correlation between the constant desired array pattern and frequency dependent array pattern of isotropic elements is given for comparison (thin solid line). Antenna element spacing $d$ is defined at 5.3 GHz and presented with the input vector $\vec{\mathbf{a}}$ in each figure.

We see, that in these cases the correlation is usually clearly higher for corrected array patterns than for uncorrected. The correction increases the correlation close to one for the array with tight element spacing ($d = 0.3\lambda$). The correlation between the frequency-dependent isotropic element array pattern and the desired fixed frequency (5.2 GHz) isotropic element array pattern is presented as the reference for the correction limit. This is not the ultimate correction limit, but in the examined cases it seems to be the practical one. The general results when simulating an array of isotropic elements with real arrays of microstrip elements with the same element spacings are collected in Table II for all examined arrays. In the case of Table II the used input vector is $\mathbf{a} = [1\,1\,1\,1\,1\,1]$.

The good correction results in the case of tight element spacing show that in this case also other near field effects like metal edges causing pattern changes can be corrected simultaneously with those caused by mutual coupling as reported for the correction case in [5]. For tight spacing the good correction results are obtained also for dipole array in [12]. The more accurate correction in the case of tight element spacing was predicted using signal simulation in [1]. For some other arrays the correction results are only slightly better than noncorrected array patterns. The results in Table II show that the array with element spacing of $0.93\lambda$ gives worse correction results than the other arrays. This might be due to the fact, that this array has the largest ground plane, which causes more rippled antenna element patterns.

The presented results show also, that a microstrip array can simulate an array of isotropic antenna elements better when the element spacing in the desired array is smaller than that in the real array. This effect is detected in the cases of element spacing about $d = 0.5\lambda$ [see Fig. 4(a) and (b)]. In these cases the use of a desired array pattern of isotropic elements generated for higher frequencies than 5.2 GHz (up to 5.5 GHz) is shown to give better correlation results when the correction matrix is calculated for measured patterns at 5.2 GHz and used at the frequency band from 5.0–5.4 GHz.

## V. Conclusion

We have seen that changes caused by mutual coupling and other nonidealities in an antenna array pattern can be well corrected in a typical case with linear matrix correction. Both LSE-type and scattering matrix-based correction methods were studied and the LSE method seemed to be clearly better for small microstrip arrays. Linear correction gives good results in the sense of correlation between desired and corrected patterns for microstrip antenna arrays with different types of desired element patterns. This is a great advantage, because the microstrip antenna array is compact and simple to manufacture.

TABLE II
CORRELATION AT 5.0–5.4 GHz BETWEEN SOME FREQUENCY-DEPENDENT ARRAY PATTERNS AND THE RESPECTIVE FIXED DESIRED ARRAY PATTERN. THE INPUT VECTOR IS $\vec{a} = [1\ 1\ 1\ 1\ 1\ 1]$

| Array properties | | Correlation between desired array pattern of isotropic antenna elements at 5.2 GHz and frequency dependent array with element pattern type of | | | | | |
|---|---|---|---|---|---|---|---|
| | | Isotropic | | Measured | | Corrected | |
| $d/\lambda$ | others | min | max | min | max | min | max |
| 0.30 | *), 1B), 2A) | 0.998 | 1.000 | 0.952 | 0.984 | 0.987 | 1.000 |
| 0.48 | *), 1B), 2A) | 0.995 | 1.000 | 0.945 | 0.984 4) | 0.957 | 0.990 4) |
| 0.48 | 1A), 2A) | 0.995 | 1.000 | 0.963 | 0.988 4) | 0.968 | 0.989 4) |
| 0.50 | 1A), 2B) | 0.994 | 1.000 | 0.980 | 0.990 4) | 0.985 | 0.994 |
| 0.93 | 1B), 2A), 3) | 0.931 | 1.000 | 0.820 | 0.908 | 0.834 | 0.920 |

*) Results are presented fully in Fig. 5
1A) usual periodical array, 1B) antenna array with symmetrized input ports
2A) horizontal polarization, 2B) vertical polarization
3) the substrate plate is larger than for other arrays
4) the maximum correlation is reached at 5.0 GHz, which is the lowest used frequency

The study of array pattern correction over a frequency band indicated, that the correction matrix is fairly insensitive to changes in frequency.

The LSE method used as the preferred method here is not the only valid basis for correction. However, it seems to be the most general and robust method. In some cases of adaptive antenna array design the zero directions are pronounced [32]. Thus the null displacement and cancellation is more problematic for adaptive antenna array use than other nonidealities. In that case some other than the LSE criterion is needed like, for example, different weights for different pattern directions.

The array pattern of isotropic elements, which was mostly used as the desired pattern, is not optimal for all beams in different directions for the examined arrays, because the microstrip array element directivity is largest in the front direction. However, for wide-angle adaptive use the antenna directivity in broadside direction is not a primary pattern synthesis goal. Furthermore, the corrupting effect of mutual coupling on antenna array element patterns is usually ignored in adaptive algorithms [33], in which the isotropic element pattern is a standard, well known pattern. Thus the results with correction applied to arrays with isotropic elements show, that microstrip arrays can be used widely in adaptive antenna systems.

To have a compact array the element spacing and substrate size should be minimized. The results show, that in microstrip arrays the substrate edge effect (diffraction) on antenna element patterns can be corrected together with those caused by mutual coupling, if the element spacing and ground plane are small, which is the practical situation for small adaptive base station antenna arrays. The reflected power is also a problem in microstrip arrays [19]. With closer element spacing the correction results are so good, that it seems to be realistic to repair the array pattern only partially and minimize at the same time the increased reflected power, caused mainly by lowered pattern orthogonality.

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