Investigation of Different Low-Cost Array Antennas for Digital Beamforming and DOA-Estimation

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Abstract

This contribution presents two different 10 GHz low-cost microstrip array antennas. First an array of U-slot patch elements is investigated which exhibits a large bandwidth of ~35%. Secondly a semi-circular microstrip array on a planar metallic reflector with an extended beam scanning range of ±70° is discussed. For both types of arrays measurement results are presented. Suitable algorithms for the calibration of the U-slot patch array and the transformation of the semi-circular microstrip array to a uniform virtual linear array are investigated. In addition to the well known procedures, a modification to the commonly used calibration method is introduced and applied to the measured data.

1 Introduction

Increasing requirements in data rate and subscriber mobility in future telecommunication systems lead to the need of more capable and cost-efficient smart antenna systems. Printed antennas are usually low-cost and easy to integrate into any circuit environment. However, the typical microstrip antenna is narrowband and its beam scanning capabilities are poor due to the narrow-beam element pattern.

This contribution investigates the properties of a uniform linear array of four U-slot patches (ULA-UP) that exhibits a large bandwidth and a semi-circular microstrip array (SCMA) of series fed patch rows on a planar metallic reflector with an extended beam scanning range. Both arrays are designed to operate at 10 GHz and characterized with a multi-channel measurement receiver. The fabricated arrays and measurement receiver are shown in detail in the next chapter.

Adaptive array signal processing algorithms are usually applied to ideal uniform linear arrays. In practice, the presence of mutual coupling and various near-field effects demand for suitable calibration methods. Moreover in the case of the SCMA the lack of the nonuniformity is circumvented by the use of a suitable transformation to a uniform virtual linear array (UVLA). These methods and its application to the measured data are dicussed in chapter 3.

2 Investigated Arrays and Measurement Setup

2.1 U-Slot Patch Array

Several methods have been introduced to increase the bandwidth of microstrip antennas. One of these types is the single layer U-slot microstrip patch [1]. It is a probe fed patch with a U-shaped slot inside the patch metallization. Fig. 1 shows the uniform linear array of four U-slot patches.

The most important parameter to increase the bandwidth of this antenna is the comparatively thick RT/duroid 5880 substrate of 125 mil. Probe-feeding a patch antenna on a thick substrate usually leads to high inductive components in the input impedance. These are compensated by a capacitive effect, realized by the U-shaped slot.

Fig. 2 shows the simulated input return loss for a single element and the corresponding measurement data of the four array elements. The method of moments (MoM) simulation result and the measured data are in very good agreement and exhibit a large -10 dB bandwidth of ~35%.

Fig. 1: Linear array of four λ/2 spaced U-slot patches.

Fig. 2: Simulated (MoM) and measured return loss of the U-slot patch elements in the ULA-UP.
The measured element patterns of the array elements are shown in Fig. 3. The significant differences between the patterns of the elements indicate a noticeable influence of mutual coupling as well as the finite size of the ground plane and the substrate.

![Fig. 3: Measured element pattern for the elements of the ULA-UP in Fig. 1.](image)

2.2 Semi-Circular Microstrip Array

For wide-angle scanning applications, the semi-circular microstrip array (SCMA) on a planar metallic reflector is investigated in [2]. It combines the favorably beam-scanning properties of cylindrical microstrip arrays with the typical advantages of microstrip antennas. Fig. 4 shows the array configuration that consists of eight series-fed microstrip patch rows, each of six patches, on a 31 mil RT/druoid 5870 substrate. The substrate is fixed on the aluminium cylinder with a radius of $R=5/3\lambda_0$ by gluing. The patch rows are connected at the center to a semi-rigid coaxial line and the measured -10 dB bandwidth of the rows is ~3%.

Fig. 5a depicts the element patterns for the four patches on one quadrant of the investigated eight element array according to the analytical model, introduced in [2]. The element position on the cylinder is given by the angle $\Phi_n$. Because of symmetry, the patches on the other quadrant show the identical, but mirrored characteristic.

The corresponding measurement results in Fig. 5b show some ripple around 0°, which is attributed to be an artefact of standing waves between the feeding antenna and the metallic reflector.

![Fig. 4: SCMA on a metallic reflector (13$\lambda_0 \times 10\lambda_0$) with 8 separate controled series-fed patch rows.](image)

![Fig. 5: a) Simulated and b) measured element pattern for the SCMA-configuration in Fig. 4. $\Phi_n$ is the position of the element on the cylinder.](image)

![Fig. 6: Maximum achievable directivity for a SCMA on a planar reflector and a comparable linear array. SCMA: 8 elements, $R=5/3\lambda_0$. Linear array: 8 elements, $\lambda_0/2$ spacing. Moreover, for larger angles the measured data is slightly below the theoretical pattern. This is due to the finite size of the reflector. However, the comparison between the analytical model and the measured pattern exhibits good agreement. The maximum achievable directivity with this array in dependence of the scan angle $\Phi_0$ is calculated from the simulated and the measured element patterns and shown in Fig. 6. In addition, the directivity as a function of $\Phi_0$ for a corresponding linear array of 8 patch elements is shown for comparison. The achievable average directivity that results from the simulated ideal element patterns is about 12.3 dBi and an angular scanning range of ±77° is obtained theoretically. Assuming the same directivity value, the angular scanning range of the linear array is about ±47°. Due to the reduced element patterns at the larger scan angles, the measured scanning range is reduced to ±70°. However, for the SCMA, the scanning range is](image)
extended by 50%, while the mean directivity value is only slightly decreased by about 2 dB compared to the linear array.

2.3 Measurement Receiver

To investigate the properties of different types of array antennas and suitable algorithms for beamforming, direction of arrival (DOA)-estimation and array-calibration, a measurement receiver with 16 separate receiver branches has been realized. Fig. 7 shows the block diagram of a single receiver branch.

Fig. 7: Block diagram of the measurement receiver.

The signals received by each antenna element are converted from the X-band to an intermediate frequency of f_{IF} = 71 MHz. After amplification and filtering by a surface acoustic wave filter, the signal is I/Q-demodulated. The A/D-conversion of the baseband signals is done with a National Instruments PC-board at a maximum sampling rate of 40kS/s.

3 Calibration and Transformation

Array signal processing algorithms are usually applied to ideal uniform linear arrays. To compensate undesired electromagnetic effects like mutual coupling and near-field scatterers, different algorithms for the calibration of array antennas have been proposed, e.g. [3]. Basically they determine a calibration matrix to calculate the ideal array output vector from the measured one.

To circumvent the lack of the nonuniformity of array antennas, a preprocessing technique is proposed in [4]. A matrix is determined to transform a N-element nonuniformly spaced array on to a N'-element UVLA within a predefined angular sector. Note that N' is not necessarily equal to N and that this is not an exact transformation, but it is a best-fit approximation, that equals the classical calibration approach.

In both cases the calibration or transformation matrix is determined by performing reference measurements at L calibration angles which gives L steering vectors that are combined in a N×L steering matrix

\[ A_{rad} (\phi) = [\hat{a}_1 (\phi) \cdots \hat{a}_L (\phi)] . \]  

The corresponding ideal steering matrix, determined by the geometry of the desired ideal array, is linked to the measured data via the calibration matrix:

\[ A_{rad} = C \cdot A_{rad} \cdot \hat{A}_{rad} . \]  

The calibration matrix is then determined by the calculation of the pseudo inverse of the measured steering matrix [3].

\[ C = \left[ A_{rad} \cdot \hat{A}_{rad} \cdot \left( A_{rad} \cdot \hat{A}_{rad} \right)^{-1} \right] L \geq N \\{ \text{diag} \{ a_i \} \cdot \text{diag} \{ \hat{a}_i \} \}^{-1} L = 1 \]  

If element coupling and pattern inhomogeneity have only low influence, it turns out to be sufficient to determine only the elements of the main diagonal of C with only \( L = 1 \) reference measurement.

In the case of small arrays, \( N \) is usually small compared to \( L \) and hence, this method delivers a highly overdetermined set of equations. In [5] it is demonstrated that this concept may not work well with small arrays. To increase the degrees of freedom, by increasing the number of unknowns in this set of equations, the calibration with the measured steering vector and its complex conjugated is proposed. In this case, the new steering matrix becomes

\[ B = \left[ A_{rad} \hat{A}_{rad} \right] \]  

and the calibration matrix is calculated by

\[ C = A_{rad} \cdot B^H \left( B \cdot B^H \right)^{-1} . \]

To evaluate the performance of these calibration and transformation methods the error function

\[ err = |\Phi_{MEAS} - \Phi_{MUSIC}| \]  

is defined, where \( \Phi_{MEAS} \) is one of the \( L \) calibration angles and \( \Phi_{MUSIC} \) is the estimated angle of arrival using MUSIC algorithm [6].

3.1 Calibration of the ULA-UP

The resulting direction of arrival estimation error \( err \) for the calibration of the ULA-UP is shown in Fig. 8 for a different number of reference measurements \( L \) and for the case of the additional use of the complex conjugated steering matrix.

Fig. 8: DOA-estimation error \( err \) after calibration of the ULA-UP.
The mean value of \(err\) within the calibration range of ±48° and within the complete angular range of ±60° is listed in Tab. 1.

### Tab. 1: Mean estimation error \(err\).

<table>
<thead>
<tr>
<th>(L)</th>
<th>(1)</th>
<th>(17)</th>
<th>(17 – \text{conj})</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean_{tot} ({err})</td>
<td>2.09</td>
<td>1.66</td>
<td>1.51</td>
</tr>
<tr>
<td>mean_{tot} ({err})</td>
<td>-</td>
<td>0.92</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Even the calibration with only a single reference measurement \((L=1)\) at 0° that compensates mainly gain and phase errors of the receiver branches, is successful and gives a mean estimation error of about 2°. A highly overdetermined set of equations is given in the case \(L=17\).

Here a mean error below 1° can be achieved within the calibration range. A further increasing of \(L\) does not lead to a reduced mean value error in this study. If the complex conjugated data is used additionally \((L=17-\text{conj})\) as described above, the mean error can be reduced to about 0.5°, what is within the accuracy of the measurement setup.

### 3.2 Transformation of the SCMA

Applying the transformation according to [4] of the SCMA to a UVLA works well for angular sectors of up to 90°. However, the transformation within the SCMAs angular scanning range of ±72° is not successful with this approach, whereas the use of the complex conjugated of the measured data gives good results. As already mentioned before, the number of elements in the UVLA \(N^o\) must not necessarily equal to the number of elements in the SCMA \(N=8\). The influence on the transformation result is shown in Tab. 2 for a fixed angular transformation range of ±72° in steps of 6°.

### Tab. 2: Mean estimation error \(err\) in dependence of \(N^o\) in the UVLA.

<table>
<thead>
<tr>
<th>(N^o)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean_{tot} ({err})</td>
<td>1.5</td>
<td>1.1</td>
<td>0.8</td>
<td>1.2</td>
<td>1.3</td>
<td>1.7</td>
<td>2.3</td>
</tr>
</tbody>
</table>

The mean error becomes a minimum for \(N^o=4\) and the corresponding plot is shown in Fig. 9. It is clear that \(N^o\) must be less than \(N\), because depending upon the angle of arrival, only a reduced number of elements contribute to the array output.

![Fig. 9: DOA-estimation error \(err\) after transformation of the SCMA on a UVLA with \(N^o=4\).](image)

### 4 Conclusions

Two different types of microstrip arrays with a center frequency of 10 GHz have been investigated. The four elements of the ULA-UP show a relative -10 dB bandwidth of ~35% and the measured return loss agrees well with the simulated data. Therefore, the U-slot patch antenna is an interesting candidate for broadband, low-cost communication system. The SCMA on a planar metallic reflector exhibits a scanning range of ±70° what is an improvement of at least 50% compared to a corresponding linear patch array, while the maximum directivity is only slightly reduced. Hence, this configuration is particularly well suited for wide-angle scanning applications in communication and sensor systems.

To overcome various undesired electromagnetic effects like mutual coupling and scatterers in the near-field of the antenna as well as the lack of the nonuniformity in the case of the SCMA, different calibration or transformation procedures have been investigated. The algorithms have been evaluated by comparing the real angle of arrival with the estimated value by using the MUSIC algorithm with the corrected steering vectors. It turned out that using the measured steering vector and its complex conjugated value for the calculation of a calibration or transformation matrix will reduce the resulting error of the DOA-estimation.

### 5 References


