Development of an Adaptive and a Switched Beam Smart Antenna System for Wireless Communications

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Abstract

This study concentrates on the development of two separate Smart Antenna Systems for the 2.45GHz ISM band. Both systems incorporate the RF-beamforming method. Each system has the ability to point the beam in a three dimensional space, both in azimuth and in elevation direction. The Switched Beam System adopts a passive network-based beamforming approach, using 2-D Butler matrix topologies. The Adaptive System utilizes the vector modulator method, but only in the azimuth direction, increasing beam-steering accuracy, whereas introducing complexity and cost. The system design is presented for both cases, along with some module design and testing examples. A comparison of the two systems will be also discussed.

Introduction

SDMA (Space Division Multiple Access) is a new technique that aims to improve the capacity and quality of wireless systems. It is based on the use of steerable antennas, incorporating electronically controllable Beamforming Networks (BFNs). New standards for Switched Beam and Point-to-Multipoint Smart Antenna Systems are under development by ETSI (European Telecommunications Standards Institute), [1]. Beamforming networks can be developed either at RF or IF level. The use of IF-BFNs results in a Smart Antenna System fully exploiting the advantages of an Adaptive Antenna. Also, their implementation and control are easier. However, IF-BFNs suffer from increased complexity, since they are incorporated into a multichannel topology requiring the development of the system from scratch. On the other hand, RF-BFNs offer decreased complexity, but harder control requirements. Similarly, RF-Beamforming Networks exploit only some of the Smart Antenna Systems capabilities. Their critical advantage is the easy integration with the existing architectures in Base Stations (retro-fit), since only the replacement of the RF front-end is needed. Since the RF-Beamforming method has been adopted, the critical point is the use of either passive or active beamformers. Once again, active beamformers offer more capabilities and particularly higher beam pointing accuracy than the passive BFNs. But, the active BFNs introduce non-linearities, difficulties in achieving the desired dynamic range and their most serious drawback is their non-reciprocal nature. Namely, separate active RF-BFNs are required for the transmitter and receiver RF-stages. In contrary, passive RF-BFNs can be reciprocal and linear, retaining the system dynamic range.

The Switched Beam System

The proposed Switched Beam System uses the Butler matrix network for the beamforming procedure, [2,3,4,5]. The system’s basic demand is the pointing of the beam both in azimuth and in the elevation direction. For this reason, two alternative system topologies are considered. The first proposed system consists of an 8x8...
printed Butler matrix producing 8 orthogonal beams in the azimuth direction, covering a 120° sector. At each output port of the $8 \times 8$ network, a $4 \times 4$ Butler matrix is connected, producing consequently 4 orthogonal beams covering an elevation angular sector. The cascaded operation of the two networks produces 32 discrete beams in space. The proper input port of each matrix is chosen using digitally controlled MMIC switches (SP8T and SP4T). The block diagram of the system is presented in Figure 1(a). The disadvantage of this first topology is the wide beamwidth in the elevation direction ($\sim 30°$). This is due to the small number of vertical antenna elements (only four). The second system topology considers 8 antenna elements in the elevation direction, fed by an $8 \times 8$ matrix, which offers the desired beamwidth ($\sim 15°$). In this case, only 4 beams from the 8 available will be practically used, reducing the scanning sector to about 60°. This result is in agreement with the desired specifications. The block diagram for this case is presented in Figure 1(b). An alternative approach under consideration is to use 8 antenna elements in the vertical direction which will be fed in pairs (same phase) by a $4 \times 4$ Butler matrix. It must be emphasized that there is no need for circulators since the whole antenna system is reciprocal. Moreover, this smart antenna is passive (without amplifiers), thus, preserves the system dynamic range and it does not cause any gain stability or other spectrum problems [1].

Figure 2: Block diagram of the DOA subsystem.  
Figure 3: Simulated results for the DOA voltage signals.

Furthermore, the required Direction Of Arrival (DOA) information of the received signal is provided by a separate subsystem to a microcontroller unit, which also controls the MMIC switches. The block diagram of the subsystem is shown in Figure 2. Figure 3 presents the simulated results for the DOA error voltage signals. The DOA is extracted from these two voltage curves.

Figure 4: Simulated results for the azimuth and elevation orthogonal beams produced by the systems of Fig.1 (a) 8 beams produced in the azimuth direction for both cases, (b) 4 beams produced in the elevation direction by the system of Fig.1(a), (c) the reduced angular sector used by the system of Fig.1(b)

In Figure 4(a), the 8 orthogonal beams produced in the azimuth direction for both systems of Figure 1 are presented. Figure 4(b) shows the 4 orthogonal beams produced in the elevation direction by the system of Figure 1(a). The elevation angular sector which will be practically used in Figure 1(b) case is shown in Figure 4(c).

The system presented in Figure 1(b) is the appropriate, as it is seen from Figure 4, since it combines increased accuracy in both directions, accomplishing the desired specifications in the elevation angular sector.

The next step is the design of the Butler matrix beamformers. Both $4 \times 4$ and $8 \times 8$ Butler matrix networks were designed. The block diagrams of the $4 \times 4$ and $8 \times 8$ Butler matrices are shown in Figure 5.

Both networks were developed in microstrip form, printed on a 20mil Rogers-4003 dielectric substrate with
Figure 5: Block diagrams of the $4 \times 4$ and $8 \times 8$ Butler matrix networks. (a) $4 \times 4$ Butler matrix, (b) $8 \times 8$ Butler matrix.

Figure 6: Microstrip layouts of the $4 \times 4$ Butler matrix network.

$\varepsilon_r = 3.38$ and $\tan \delta = 0.0021$. Figure 6 presents three different layout configurations of the $4 \times 4$ Butler matrix network that were designed.

Table 1: Phase differences at antenna ports when the 2R port of Figure 6(b) network is activated.

<table>
<thead>
<tr>
<th>Phase Difference (deg)</th>
<th>Ideal</th>
<th>Simulated</th>
<th>Measured</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ant2-Ant1</td>
<td>-135</td>
<td>-134.9</td>
<td>-139.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Ant3-Ant2</td>
<td>-135</td>
<td>-134.9</td>
<td>-131.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Ant4-Ant3</td>
<td>-135</td>
<td>-135</td>
<td>-138.9</td>
<td>2.9</td>
</tr>
</tbody>
</table>

The most preferable layout is that of Figure 6(b), since it keeps all input and output ports on the same side, using crossovers (or cross couplers), [6]. The distance between output-antenna ports is kept equal to $\lambda_0/2$. The layout of Figure 6(c) was designed as an alternative for a circular array.

The proper function of the beamformer results in the proper beam-steering performance of the system. Figure 7 presents the measured results for the S-parameter magnitudes of the network in Figure 6(b), when the 2R port is activated, generating the corresponding beam. The theoretical value for the amplitude distribution is -6dB. Moreover, Table-1 shows the ideal, simulated and measured values of phase differences between antenna ports.

For the $8 \times 8$ matrix, only simulated results will be presented. The microstrip layout of the network is shown in Figure 8, whereas Figure 9 presents the simulated S-parameter magnitudes for the case of the 3L port activation in Figure 8. The corresponding theoretical value for the amplitude distribution is -9dB. Some losses are observed, but they are due to the relatively large size of the network.
Table 2: Phase differences at antenna ports when the 3L port of Figure 8(h) network is activated.

<table>
<thead>
<tr>
<th>Phase Dif (deg)</th>
<th>Ant2-Ant1</th>
<th>Ant3-Ant2</th>
<th>Ant4-Ant3</th>
<th>Ant5-Ant4</th>
<th>Ant6-Ant5</th>
<th>Ant7-Ant6</th>
<th>Ant8-Ant7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>112.5</td>
<td>112.5</td>
<td>112.5</td>
<td>112.5</td>
<td>112.5</td>
<td>112.5</td>
<td>112.5</td>
</tr>
<tr>
<td>Simulated</td>
<td>111.7</td>
<td>114.8</td>
<td>110.9</td>
<td>111.5</td>
<td>113.7</td>
<td>112.5</td>
<td>111.8</td>
</tr>
<tr>
<td>% error</td>
<td>0.7</td>
<td>2.0</td>
<td>1.4</td>
<td>0.9</td>
<td>1.0</td>
<td>0.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Consequently, Table 2 shows the ideal and simulated phase differences between antenna ports, when the 3L port is activated.

**The Adaptive RF-BFN System**

The proposed system combines the idea of an Adaptive in azimuth and a Switched Beam System in the elevation direction. In order to achieve all the advantages introduced by an Adaptive System, but also to keep the cost at an affordable level, the architecture shown in Figure 10 is chosen.

In the azimuth direction, vector modulators are used for the beam-steering. The pointing of the beam in the elevation direction is accomplished through the use of Butler matrices, as in the Switched Beam System. The I-Q control of vector modulators allows the reduction of the sidelobe level, while being able to accurately point the antenna beam in any direction. Moreover, the introduction of radiation pattern nulls toward the direction of any undesirable interferer is also possible (null steering). In order to improve the sidelobe level, the relative magnitude distribution of the antenna elements in the azimuth direction presented in Table 3 is introduced. This is a triangular aperture distribution.

Table 3: Triangular aperture distribution in the azimuth direction.

<table>
<thead>
<tr>
<th>Element</th>
<th>1</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>Rel.Mag.Distribution</td>
<td>0.5</td>
<td>0.5</td>
<td>0.707</td>
<td>1</td>
<td>1</td>
<td>0.707</td>
<td>0.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The simulated results for the azimuth direction beamforming using the above distribution are presented in Figure 11(a). A comparison with Figure 4(a) shows considerable improvement to the sidelobe level. A sidelobe level below -20dB for most of the beams is achieved. Moreover, the scan of the beam in the azimuth direction is
achieved, through the change of the phase difference between the horizontal elements of the array. The simulated results for a part of the azimuth sector are presented in Figure 11(b).

Figure 11: Simulated results for the azimuth direction beamforming. (a) Sidelobe level reduction using the magnitude distribution of Table-3. (b) Scan of the beam for a part of the azimuth sector.

**Conclusion**

A Switched Beam and an Adaptive Smart Antenna System based on RF-BFNs have been studied. Their beamforming performance was presented. Module testing showed sufficient results. The Switched Beam System combines satisfactory beam-steering capability with simplicity, while it retains low cost, but its main advantage is its reciprocal and passive nature which preserves the system dynamic range. The Adaptive System offers improved performance, but harder functionality and control, in addition with increased cost. Concluding, the Switched Beam Systems constitute a good solution for the next generation SDMA schemes.

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**REFERENCES**