Studienarbeit:
Planar Multi-Beam Antenna for W-LAN

Presented by
Wu, Liangjun

Supervisor
Prof. -Dr. - Ing. K. Solbach

Duisburg
19. 11. 2007
1. Introduction

The switched-Beam antenna is one type of the small antennas, which consists of the antenna array and the beam forming network. The four-beam smart antenna generates four beams to cover 120° area.

In this thesis, we design the four-beam forming network called **Butler Matrix** (at frequency 2.4 GHz), which made of four directional coupler-power dividers (90° phase shifter) and two cross coupler (0dB). And we use microstrip antennas as array elements.

For a special requirement, we can reduce the element spacing and bend the planar substrate carrying the radiator elements, to get coverage of a full 180° angular in azimuth (hemisphere).
4×4 Butler Matrix

- patch_antenna
- Microstrip
- Cross over
- Phase shifter
- -90° couple
- feed-port

<table>
<thead>
<tr>
<th>y1</th>
<th>y2</th>
<th>y3</th>
<th>y4</th>
<th>Main beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>-45</td>
<td>-135</td>
<td>-90</td>
<td>-180</td>
<td>1R</td>
</tr>
<tr>
<td>-135</td>
<td>0</td>
<td>-225</td>
<td>-90</td>
<td>2L</td>
</tr>
<tr>
<td>-90</td>
<td>-225</td>
<td>0</td>
<td>-135</td>
<td>2R</td>
</tr>
<tr>
<td>-180</td>
<td>-135</td>
<td>-90</td>
<td>-45</td>
<td>1L</td>
</tr>
</tbody>
</table>
2. Patch Antenna

• 2.1 Transmission-Line Model

Fringing Effekt
Leff = L + 2 \cdot L
L: physical Length
Leff: effective Length
\[
\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}}
\]

\[
\frac{\Delta L}{h} = 0.412 \left( \frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258} \right) \left( \frac{W}{h} + 0.264 \right) \left( \frac{W}{h} + 0.8 \right)
\]

\[
L = L_{\text{eff}} - 2 \Delta L
\]

\[
L_{\text{eff}} = \frac{\lambda_{\text{eff}}}{2} = \frac{1}{2} \frac{C_0}{fr \sqrt{\varepsilon_{\text{reff}}}}
\]

h: Thickness of Substrate    W: Width of Patch    fr:Resonant Frequency
2.2 Antenna Design procedure

a) The substrate we have is ROGER4003, with

\[ \varepsilon_r = 3.38, \, h = 0.51\text{mm (35um Cooper)}, \, \tan\delta = 0.0027 \]

b) For an efficient radiator, we let

\[ W = \frac{v_0}{2fr} \sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{3 \times 10^8}{2(2.4 \times 10^9)} \sqrt{\frac{2}{3.38 + 1}} = 42.23\text{mm} \]

c) Using Transmission-Line Model, we have

\[ \varepsilon_{eff} = \frac{3.38 + 1}{2} + \frac{3.38 - 1}{2} \left[ 1 + 12 \left( \frac{0.51}{42.23} \right) \right]^{1/2} = 3.30 \]

\[ \Delta L = 0.51(0.412) \frac{(3.30 + 0.3) \left( \frac{42.23}{0.51} + 0.264 \right)}{(3.30 - 0.258) \left( \frac{42.23}{0.51} + 0.8 \right)} = 0.243\text{mm} \]

\[ L_{eff} = \frac{\lambda}{2} = \frac{1}{2 \times 2.4 \times 10^9 \sqrt{3.30}} = 34.41\text{mm} \]

\[ L = 34.41 - 2 \times 0.243 = 33.92\text{mm} \]
d) Microstrip-Line inset-length

From literature, we can approximately have $y_0$ for characteristic impedance 50 ohm

$$y_0 = \frac{L}{2 \sqrt{\varepsilon_{\text{reff}}}} = \frac{33.92}{2 \sqrt{3.30}} = 9.34 \text{ mm}$$

Let $W_f = b = 1.141 \text{ mm}$
(b: microstrip line width for 50 Ohm)

Also from (http://mwrf.com/Articles/Index.cfm?ArticleID=6993) we can get the exact inset length for 50Ohm input impedance through the mathematical model

$$y_0 = 10^{-4} \left\{ 0.001699 \varepsilon_r^7 + 0.1376 \varepsilon_r^6 - 6.1783 \varepsilon_r^5 + 93.187 \varepsilon_r^4 - 682.69 \varepsilon_r^3 + 2561.9 \varepsilon_r^2 - 4043 \varepsilon_r + 6697 \right\} \frac{L}{2}$$

$$2 \leq \varepsilon_r \leq 10$$

We have $y_0 = 9.48 \text{ mm}$
2.3 Simulation of the patch antenna
From 2.2 we have $W=42.23\text{mm}$, $L=33.92\text{mm}$, $w_f=1.141\text{mm}$, $y_0=9.48\text{mm}$ for the antenna.

Using ADS---Momentum, we draw the antenna and have the Simulation result:

Then we change the $L=34.05\text{mm}$, to get $f_r=2.4\text{GHz}$. At the same time, we must change $y_0=9.515\text{mm}$. And the simulation result is:

Finally we have $W=42.23\text{mm}$, $L=34.05\text{mm}$, $y_0=9.515\text{mm}$. And the bandwidth (at -10dB) of the antenna is approximately $B=13\text{MHz}$ (0.542%).
3. Butler-Matrix

3.1 4×4 Butler-Matrix

For Butler Matrix, from literature, we have the observation angle of the Main beam

\[ \theta = \sin^{-1}\left(-\frac{\beta}{kd}\right) = \sin^{-1}\left(-\frac{\lambda\beta}{2\pi d}\right) \]

\( \beta \) is the difference of phase between any two successive elements, which is decided by Butler-Matrix

\[ \beta = \pm \frac{\left(2i - 1\right)\pi}{N} \quad i = 1, 2, 3 \ldots \frac{N}{2} \]

\( d \) is the spacing between antennas, by reducing the \( d \), we can have bigger \( \theta \)

For a 4×4 Butler-Matrix, we have \( N=4 \), we let \( d = \frac{\lambda}{2} \)

Then we can calculate the observation angle of the Main beam (\( \theta \))
4×4 Butler-Matrix

<table>
<thead>
<tr>
<th></th>
<th>x1</th>
<th>x2</th>
<th>x3</th>
<th>x4</th>
<th>β</th>
<th>θ</th>
</tr>
</thead>
<tbody>
<tr>
<td>y1</td>
<td>-45°</td>
<td>-90°</td>
<td>-135°</td>
<td>-180°</td>
<td>-45°</td>
<td>14.5° (1R)</td>
</tr>
<tr>
<td>y2</td>
<td>-135°</td>
<td>0°</td>
<td>-225° (135°)</td>
<td>-90°</td>
<td>135°</td>
<td>-48.6° (2L)</td>
</tr>
<tr>
<td>y3</td>
<td>-90°</td>
<td>-225° (135°)</td>
<td>0°</td>
<td>-135°</td>
<td>-135°</td>
<td>48.6° (2R)</td>
</tr>
<tr>
<td>y4</td>
<td>-180°</td>
<td>-145°</td>
<td>-90°</td>
<td>-45°</td>
<td>45°</td>
<td>-14.5° (1L)</td>
</tr>
</tbody>
</table>
3.2 3dB 90°Hybrid Coupler and Cross Coupler

Using ADS---LineCalc
a) For Z0=50 Ohm, W=1.141mm
b) For $Z_0 = \frac{50}{\sqrt{2}}$ Ohm, W=1.932mm

3.2.1 3dB 90°Hybrid Coupler

90° hybrid coupler built around transmission lines

The optimized 90°Hybrid Coupler (mm)
And the simulation result of the Hybrid Coupler is

As expected, the phase difference between port 3 and port 2 is 168.849-(-101.231)=270.08 (-89.92) degrees.
And the dB(S(2,1)) dB(S(3,1)) are close to -3dB.
3.2.2 Cross Coupler

0dB Cross Coupler build around transmission lines

The optimized Cross Coupler (mm)
Simulation results of the Cross Coupler

The insertion loss for the coupled port is $\text{dB}(S(3,1)) = -0.093$ dB while isolation ports are smaller than -30 dB
3.3 Optimization and simulation of 4×4 Butler-Matrix Network

The left and the right parts of the Butler Matrix are symmetric, so we can just consider the left side of the Butler Matrix. Now we divide the left side into 2 Parts: PART1 (BOTTOM) and PART2 (TOP).

Two Parts of the Butler Matrix (Bottom and Top)
3.3.1 Part 1 (Bottom)

a) Simulation of the right side Phase $(S(3,1))=-129.140^\circ$

b) We can calculate $h=19.4818\text{mm}$ (the same height with right)

c) $S=S_{31}-S_{21}$ should be $-45^\circ$, allow $L$ to vary, set the optimization $S_{21}=-84.14^\circ$ After optimization we have $L=25.61\text{mm}$. 
3.3.2 Part2: (Top)
a) Consider right side of the Top, we must let $L1=10.8989\text{mm}$ to get the spacing between antennas

$$d = \frac{\lambda_0}{2} = \frac{1}{2} \frac{C_0}{fr} = 62.5\text{mm}$$

b) Then we have simulation result $S31=-170.987^\circ$
c) Consider the left side, we can calculate $L_2=20.721\text{mm}$, we must let $L_1=49.861\text{mm}$ to get the space between antennas $d=62.5\text{mm}$

d) We have simulation result $S_{21}=-78.783^\circ$

e) We have $S_{31}=-170.987^\circ$ and $S_{21}=-78.783^\circ$.

Then we have $S=S_{31}-S_{21}=-92.2037^\circ$ (Target: $-90^\circ$)
f) This means we should increase \( S21 = -2.2037^\circ \)
(also \( L21 = 0.4708 \text{mm} \)). \( E_s \) is difficult such a short length to increase with bends.

g) Then we have 2 choices:

(1) Increase \( S21 = -2.2037^\circ - 360^\circ = -362.2037^\circ \)
(also \( L21 = 77.3799 \text{mm} \))

(2) Increase \( S31 \), then increase \( S21 = S31 + (-2.2037^\circ) \)

h) We choose (2), we first increase \( S31 \) (arbitrarily), we have the simulation result \( S31 = 145.302^\circ \)

The top of the Butler-Matrix
i) Then we setup the goal of the optimization $S_{21} = -124.698^\circ$ ($S = -90^\circ$). After optimization we can confirm the design of the left side.
3.4 Simulation of the Butler Matrix Network

From 3.3 and symmetry of the Butler Matrix, we have the Butler Matrix Network.
The simulation results are shown in the Table

<table>
<thead>
<tr>
<th></th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>126.272</td>
<td>84.418</td>
<td>39.043</td>
<td>-6.513</td>
<td>-45</td>
</tr>
<tr>
<td>P2</td>
<td>38.422</td>
<td>171.941</td>
<td>-54.383</td>
<td>83.405</td>
<td>135</td>
</tr>
<tr>
<td>P3</td>
<td>83.361</td>
<td>-54.481</td>
<td>171.935</td>
<td>38.387</td>
<td>-135</td>
</tr>
<tr>
<td>P4</td>
<td>-6.516</td>
<td>38.985</td>
<td>84.435</td>
<td>126.237</td>
<td>45</td>
</tr>
</tbody>
</table>

The phase difference between input and output (°)

a) For input P1, we have Phase difference -41.854°, -45.375°, -45.556°
b) For input P2, we have Phase difference 133.519°, -226.324° (133.676°), 137.788°
c) For input P3, we have Phase difference -137.842°, 226.416° (-133.584°), -133.548°
d) For input P4, we have Phase difference 45.501°, 45.45°, 41.802°
3.5 The simulation results of Butler-Matrix (with antennas)
We have already the network of the Butler Matrix. Now we just add the 4 patch antennas (see 2.3)
The simulation results are

- $m_1$: $\text{freq} = \text{dB}(S(1,1)) = -47.25$ dB, $\text{Min} = 2.398$ GHz
- $m_2$: $\text{freq} = \text{dB}(S(2,2)) = -35.84$ dB, $\text{Min} = 2.400$ GHz
- $m_3$: $\text{freq} = \text{dB}(S(3,3)) = -37.73$ dB, $\text{Min} = 2.400$ GHz
- $m_4$: $\text{freq} = \text{dB}(S(4,4)) = -42.01$ dB, $\text{Min} = 2.398$ GHz
Using Momentum---Post Processing---Radiation Pattern Control, we have 2-D Polar Far Field of the Butler Matrix

For Input P1

For Input P2

For Input P3

For Input P4
4. Manufacture and test of the Butler Matrix

4.1 Manufacture of the Butler Matrix

We define the cutline of the Butler-Matrix, then expert this design as Gerber file, send the file cond.gbr to the factory to produce the Board.
Then we have the finished Butler-Matrix with 4 coupled devices
4.2 Test results of the Butler Matrix

Antenna diagram of Butler Matrix for input P1 (Polar)
Antenna diagram of Butler Matrix for input P2 (Polar)
Antenna diagram of Butler Matrix for input P3 (Polar)
Antenna diagram of Butler Matrix for input P4 (Polar)
We have

<table>
<thead>
<tr>
<th></th>
<th>(theoretic) $\theta_i$</th>
<th>(simulation) $\theta_i$</th>
<th>(test) $\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>14.5°</td>
<td>12°</td>
<td>12°</td>
</tr>
<tr>
<td>P2</td>
<td>-48.6°</td>
<td>-42°</td>
<td>-39°</td>
</tr>
<tr>
<td>P3</td>
<td>48.6°</td>
<td>42°</td>
<td>43°</td>
</tr>
<tr>
<td>P4</td>
<td>-14.5°</td>
<td>-12°</td>
<td>-12°</td>
</tr>
</tbody>
</table>
4.3 Test results of the Butler Matrix with bend

Now we can experimentally bend the board
For $L=30\text{mm}$, the test results are shown in Figure 34.
And for L=50mm, the test results are shown in Figure
We have

<table>
<thead>
<tr>
<th></th>
<th>Without bending</th>
<th>With bending (L=30 mm)</th>
<th>With bending (L=50 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_i$</td>
<td>Beam Width</td>
<td>$\theta_i$</td>
</tr>
<tr>
<td>P1</td>
<td>12</td>
<td>27.57</td>
<td>15</td>
</tr>
<tr>
<td>P2</td>
<td>-39</td>
<td>25.72</td>
<td>-47</td>
</tr>
<tr>
<td>P3</td>
<td>43</td>
<td>26.48</td>
<td>47</td>
</tr>
<tr>
<td>P4</td>
<td>-12</td>
<td>26.98</td>
<td>-15</td>
</tr>
</tbody>
</table>

**Analysis of the test results (degree)**

From the Table, we know that, when we increase the bend $L$, we can get bigger and bigger Beam Width. By bending of the board, we can get a bigger coverage area.
5. Conclusion

In this thesis we have designed the 4×4 Butler Matrix (at frequency 2.4 GHz), which consists of four 3dB Hybrid-Coupler, two Cross-Coupler, and four Patch-Antennas.

The test result of the Butler Matrix is just like expected. With four different inputs we can switch the direction of the main beam. (Switched-Beam antenna).

By reducing the element spacing and by suitable bending of the planar substrate carrying the radiator elements, we can get coverage of a full 180° angular in azimuth (hemisphere).
Thank you for your attention!