MODIFICATION TO BEAM STEERING ALGORITHMS IN THE PRESENCE OF DIELECTRIC LENS

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ABSTRACT

Adaptive array smart antenna involves the array signal processing to manipulate the signals induced on various antenna elements in such way that the main beam is directed towards the desired user and nulls are formed towards the interferers. A smart antenna has to meet contrasting requirements of compact form factor and high gain. A shaped dielectric lens can be used along with the antenna elements to further collimate the rays in the specified direction, improving directivity, reducing interference and significantly reducing the number of array elements. The dielectric lens also acts as a radome protecting the array from environmental effects. However there are two drawbacks with the use of dielectric lens: 1) Compensating the refractive effects of the lens in the receiving mode to obtain the true angles of arrival to locate the desired signal, and 2) Computation of the radiation pattern. This paper dwells on the first drawback viz. modification to the beam steering algorithms to estimate the true Direction of Arrival (DOA). One popular algorithm, namely, Multiple Signal Classification (MUSIC) is investigated in the presence of lens.

Keywords: Smart Antenna, Shaped Dielectric Lens Antenna, Refraction, DOA and ABF

1. INTRODUCTION

Smart antennas enable a higher capacity in wireless networks by effectively reducing multipath and co-channel interference leading to better spectrum utilization. The link rate to a mobile subscriber is dependent on the adaptive antenna system and its underlying signal processing algorithms [1, 2 and 5].

Lens provides a collimation that helps to shrink the size of a larger array, which in effect translates to a reduced RF cost [3]. But with a lens, direction of the signal received at the antenna elements is different from that of the actual angle due to refraction; hence we need an angle dependent correction factor in the steering vector to get the true angle. To obtain the correction factor, the phase change inside the lens is considered before reaching the antenna elements.[5, 10].
In this paper, ray tracing approach is used to generate the steering vector needed to implement the direction of arrival estimate algorithms. The work contribution here includes

(i) Forward ray tracing through the lens to find the actual and virtual DOA.
(ii) Analysis of critical angle of refraction.
(iii) Backward ray retrace to determine the required angle.
(iv) Progressive blindness due to critical angle.

2. FORWARD RAY TRACING

The forward ray tracing is illustrated below in figure 1.

Forward ray tracing helps in finding the angle of refraction ($r_2$) through the lens, when the angle of incidence ($\Theta$) is known. It also helps in finding the rays that will hit the antenna elements. Figure 2 below shows how the ray tracing was used to find angle of refraction through the lens for different angles of incidence. Finally it helps in finding the critical angle which is of great importance [4].

(a) Direction of angle of arrival is $20^0$

(b) Direction of angle of arrival is $30^0$

Figure 2: Forward ray tracing for different arrival angles of incidence

The parameters calculated in forward ray tracing are used for both DOA and backward ray tracing.
3. BACKWARD RAY TRACING

The backward ray tracing is illustrated below in figure 3. Here the EM rays are traced from the antenna array to outside the lens.

Once the virtual angle at each elements are calculated using forward ray tracing technique, our aim is to find true angle of incidence (in this case transmit direction) and forming beam in that direction. In the above figure,

\[ i_1 = \text{angle at which ray enters the lens} \]
\[ r_2 = \text{angle of refraction} \]

Once virtual DOA is calculated using forward ray tracing, the aim is to find true DOA using backward ray tracing.

4. CRITICAL ANGLE CONDITIONS

The critical angle corresponds to the angle, at which the ray will be reflected back from the plane surface of the lens due to total internal reflection. At the critical angle the rays will not hit the array elements. In this simulation, the number of elements and the diameter of the lens are fixed. Figure 4 below depict one such case with red vertical lines representing the antenna elements.

The refraction occurring in the lens for different arrival angles of 45\(^\circ\) and 50\(^\circ\) are as shown below in figures 5 (a) and (b) respectively.
When the rays lie above the critical angle range, all the rays are reflected back due to the phenomenon of total internal reflection from the plane surface of the lens.

As in figure 5(a) above, at an angle of $45^0$, the EM rays will just graze the surface and as in figure 5(b) at $50^0$, the total internal reflection will occur. Thus, the antenna array receives no rays to calculate the virtual DOA. As we scan off bore sight, we progress from full visibility to all elements, through a stage of partial blindness due to some elements becoming invisible to total blindness where none of the elements are visible. Under these circumstances the usage of the lens leads to loss of signal sources, especially at angles greater than $50^0$ [5,6].

Referring to figure 3 above, the critical angle can be calculated as below.

At the point $(x_2, y_2)$, bottom surface of the lens for critical angle $r_2=90^0$ and $i_2=i_{2c}$

\[
\frac{\sin r_2}{\sin i_{2c}} = \sqrt{\varepsilon_r} \tag{1}
\]

\[
\sin i_{2c} = \frac{1}{\sqrt{\varepsilon_r}}
\]

\[
i_{2c} = 90^0 - \theta_{ic} \text{ and } \theta_{ic} = \tan^{-1} \left[ \frac{y_2}{x_2 - x_1} \right] \tag{2}
\]

At the point $(x_1, y_1)$, let the critical angle be $r_c$

\[
r_c = 90^0 - \theta_{ic} - \alpha
\]

\[
\text{where } \alpha = \tan^{-1} \left[ \frac{x_1}{y_1} \right]
\]

Therefore

\[
r_c = 90^0 - \tan^{-1} \left[ \frac{y_1}{x_1 - x_2} \right] - \tan^{-1} \left[ \frac{x_2}{y_1} \right] \tag{3}
\]

\[
\frac{\sin i_c}{\sin r_c} = \sqrt{\varepsilon_r} \tag{4}
\]
Hence the critical angle is
\[ \theta_c = 90^\circ - i_c - na \]
\[ i_c = \sin^{-1}\left[\sqrt{\varepsilon_r \sin r_c}\right] \]
\[ i_c = \sin^{-1}\left[\sqrt{\varepsilon_r \sin \left(90^\circ - \tan^{-1}\left[\frac{y_1}{x_1 - x_2}\right] - \tan^{-1}\left[\frac{x_1}{y_1}\right]\right]}\right] \] (5)

5. DOA ALGORITHMS WITH LENS

The angle of arrival (AOA) using DOA algorithm is obtained in the absence and presence of dielectric lens. In the presence of lens, the AOA will be altered because of the Snell’s law applied at the boundaries of the dielectric lens. When DOA algorithm applied, it results in virtual DOA. To overcome this problem the beam steering vector is modified as per the flow chart shown in figure 6 below.

![Algorithm to obtain the correct DOA](image-url)
6. RESULTS AND OBSERVATIONS

While simulating the DOA algorithms with lens, following assumptions were made:

1. Frequency of operation be 10 GHz.
2. Direction of signal detection has a range from [-90, 90] degrees.
3. Source to be in the far-field of the antenna array with lens.
4. Number of antenna elements to be 8.
5. Inter element spacing be λ/2.
6. Dielectric lens be made of Teflon with εr = 2.08.

The results are shown in the figure 7 below.

![Figure 7: MUSIC algorithm with and without lens](image)

It can be observed from the above figure, that when lens is used for collimation, the direction of signal received at the antenna elements is different from that of actual angle and hence correction factor is needed in the steering vector to get the true angle.

7. CONCLUSION

It was shown that DOA algorithms provide better resolution and higher gain in the presence of lens, as the power of the incoming signal will be enhanced due to the collimation provided by the lens. Also, it was discussed, how corrections are added for the DOA algorithms to compensate for the refractive effects of the lens.

8. REFERENCES


