Design of a Wideband Superdirective Endfire Antenna Array Using Characteristic Modes Optimization

Hussein Jaafar, Ala Sharaiha, and Sylvain Collardey
IETR UMR CNRS 6164- Université de Rennes 1, Rennes, France
hussein.jaafar@univ-rennes1.fr,ala.shariaha@univ-rennes1.fr,sylvain.collardey@univ-rennes1.fr

Abstract

This paper presents the design of a superdirective endfire antenna array, with wideband directivity and wideband matching. The unit array element is a wideband Electrically Small Antenna, internally loaded with a non-foster circuit. By forming an endfire array of wideband elements, and by optimizing the current excitations using the theory of the Network Characteristic Modes (NCM), we were able to obtain an array with an 80% superdirectivity bandwidth, relative to the central frequency.

1. Introduction

It is well known that as the size of the antenna reduces, it tends to have an omnidirectional pattern, its efficiency decreases, and its bandwidth becomes narrower [1, 2]. By describing the radiated fields as a sum of spherical modes, Chu [1] was able to derive the lowest possible Q and the highest obtainable Gain G as a function of the antenna's size. In a similar manner, Harrington showed that the directivity can attain $N^2 + 2N$ in an antenna permitting N modes [2]. To address the directivity limit, Uzkov [3], has shown that with the proper choice of current excitation of N closely spaced isotropic elements, an endfire directivity of N^2 can be attained, such directivity represents an extraordinary "superdirectivity".

Since then, researches on small antennas were dedicated to overcome the directivity and bandwidth limitations. Recently, several topics have focused on achieving endfire superdirectivity in electrically small antenna arrays, either by fully driven arrays [3, 4], or by parasitic loaded arrays in which one element is driven and the others are either short circuited [5], or resistively loaded [6], or reactively loaded [7]. However, despite the achieved superdirectivity, these arrays exhibited a narrow bandwidth.

On the other hand, and in order to address the issue of bandwidth limitation on small antennas derived by Chu, several matching techniques were developed, especially by using active non-foster circuits loaded at the input of the antenna [8] or internally distributed inside and at the input of the antenna [9, 10].

In order to achieve superdirectivity over a wider bandwidth, the authors in [11] proposed an approach based on loading the parasitic elements of the array with Non-foster components, however, the enhanced bandwidth was limited to 2% of the central frequency. In this paper, we present a new design of an endfire superdirective antenna array, where the unit element of the array is a wideband small antenna internally loaded with a non-foster circuit. The current excitation of each array element is optimized based on the theory of the Network Characteristic Modes.

2. Design steps

The key step in our design process is the design of the unit element of the antenna array. The wide bandwidth of the designed small antenna will result in a wideband antenna array. However, in order to achieve a wideband superdirectivity, it is important to find the optimal current excitation at each port of the array. For this purpose, we use an optimization technique based on combining the NCM with an optimization algorithm [12].

Network Characteristic Modes are expressed in terms of the N-port impedance matrix of the antenna array and can be computed from the generalized eigen value problem [13]:

$$[X_a(\omega)]\bar{I}_n(\omega) = \lambda_n(\omega)[R_a(\omega)] \qquad (1)$$

Where $R_a(\omega)$ and $X_a(\omega)$ are respectively the real and imaginary part of the array's impedance matrix at the radial frequency ω . I_n is the nth eigenvector (characteristic current) and λ_n is the corresponding eigenvalue. The total current at ω is then represented as a weighted summation of the characteristic currents:

$$\bar{I}(\omega) = \sum_{n=1}^{N} \alpha_n(\omega)\, \bar{I}_n(\omega) \qquad (2)$$

Where α_n is the complex weighting coefficient of the nth mode which shows the contribution of each mode to the total current $\bar{I}$. Each characteristic current $\bar{I}_n$ radiates a characteristic field E_n. Hence, the total radiation field can also be expressed as a weighted summation of the characteristic fields as shown in (3). Therefore, α_n should be optimized such that the total radiated field $\bar{E}$ exhibits a maximal directivity. Based on the optimal α_n, the total current $\bar{I}$ is then calculated from (2). It should be noted that $\bar{I}$ is a $N \times 1$ vector, where each element represents the

current at a corresponding array port, $\bar{I} = [I_{port1}, I_{port2}, \dots, I_{portN}]$.

$$\bar{E}(\omega) = \sum_{n=1}^{N} \alpha_n(\omega)\, \bar{E}_n(\omega) \qquad (3)$$

3. Superdirective Wideband Antenna Array

3.1 Unit element

As stated in the introduction, the unit element is a wideband small antenna internally loaded with a non-foster circuit. In this example, the unit element is a Z-shaped monopole antenna, integrated on a Printed Circuit Board (PCB) of dimensions $90mm \times 35mm$, and mounted on a $0.76mm$ Rogers Duroid 5880 substrate. Figure 1 shows the geometry of the antenna, it is excited at port 1 and is loaded with a negative capacitance ($C = -0.62pF$) at port 2. Due to the non-foster load, the antenna has a bandwidth of $1.2\ GHz$, [640 MHz − 1.84 GHz] (Figure 2), and it has a directivity of 2.2 dBi at 800 MHz (Figure 3).

(a) (b)

Figure 1. (a) Geometry of the unit element. (b) zoomed view of the z-monopole.

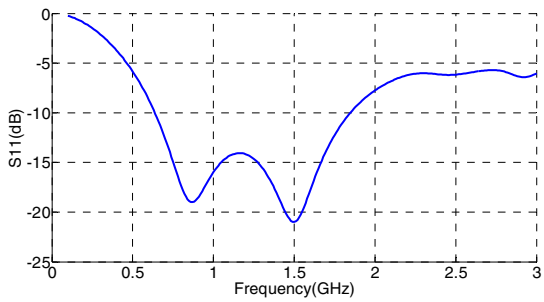


Figure 2. S11 of the antenna loaded with non-foster circuit

3.2 Endfire Two-Element Array

The geometry of the arrays is shown in Figure 4, the two elements are separated by a $5mm$ distance. Figure 5 shows the input reflection coefficient of the array which has almost the same bandwidth as the unit element. To start the optimization, the characteristic fields of the array at 800 MHz are extracted, since the arrays is a two-port network, hence there exists two characteristic field (Figure 6). After optimizing the weighting coefficients $\alpha_1$and α_2, the optimal current excitation was found to be $\bar{I} = [1e^{j170°}, 1e^{j0°}]$.

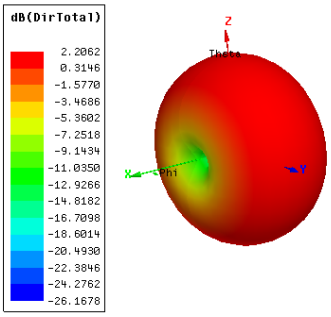


Figure 3. Directivity of the antenna at 800MHz

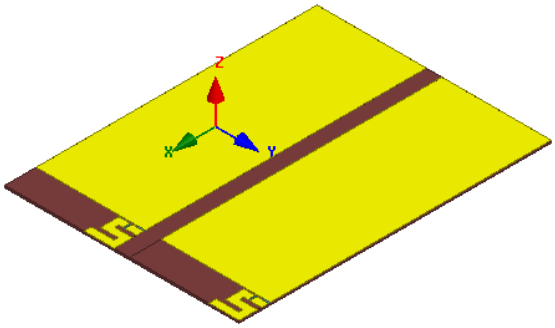


Figure 4. Endfire Two Element Array Geometry

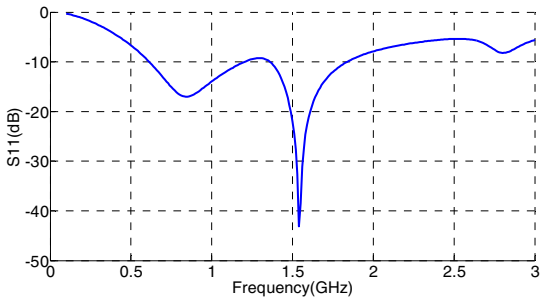
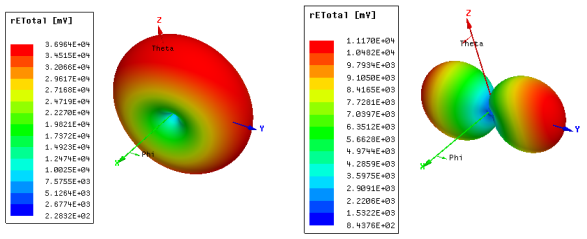


Figure 5. Input Reflection Coefficient of the Two-Element Array

With the given excitation the array has a maximal directivity of 7.1 dB in the endfire direction (φ=270°, θ=90°), at 830 MHz (Figure 7). In this endfire direction, the antenna exhibits a directivity bandwidth of 850 MHz, ($BW_{1dB} = 850\ MHz$) , from 610 MHz till 1.46 GHz. However, for a superdirective array and considering the Harrington Limit, the superdirectivity bandwidth ($BW_{superdirectivity} = 490\ MHz$) from 610 MHz till $1.1GHz$. Therfore, the array is matched and superdirective over a wide bandwidth of 490 MHz,(Figure 8). It should be noted that the directivity bandwidth is considered for a 1 dB drop from the maximum directivity ($D_{max} = 7.1\ dB$)



(a) (b)

Figure 6. Characteristic fields of the endfire array at 800 MHz. (a) First Characteristic Field E_1 . (b) Second Characteristic Field E_2.

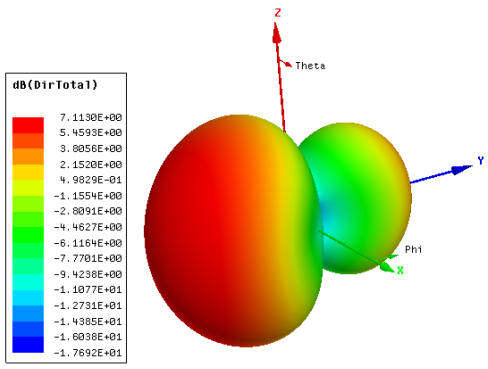


Figure 7. Directivity of the Driven Array at 830MHz.

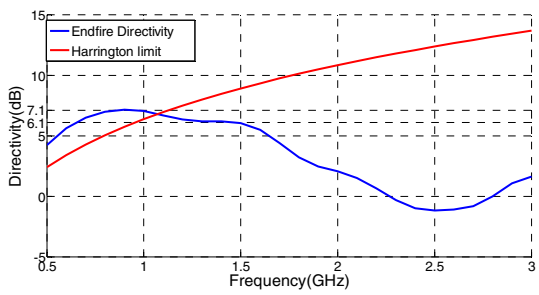


Figure 8. Comparison of the Endfire Directivity (φ=270°, θ=90°), With Respect to Harrington's Limit.

6. Conclusion

In this paper we presented a new approach to design superdirective arrays based on wideband unit elements internally loaded with non-foster circuits. With such configuration, and by optimizing the current excitations using the Network Characteristic Modes, we were able to achieve a wide bandwidth of superdirectivity ($BW_{superdirctivity} = 490MHz$) , which represents 80% of the central frequency, while maintaining a good matching.

7. References

1. L .J. Chu, "Physical limitations of omni-directional antennas," *J.Appl.Phys.*,vol. 19, no. 12,pp. 1163-1175, Dec. 1948

2. R. Harrington, "On the gain and beamwidth of directional antennas," in *IRE Transactions on Antennas and Propagation*, vol. 6, no. 3, pp. 219-225, July 1958.

3. I. Uzkov, "An approach to the problem of optimum directive antennae design", C. R. (Dokladey) Acad. Sci. l'URSS, vol. 53, no. 1, pp. 35-38,1946.

3. E. Newman and M. Schrote, "A wide-band electrically small superdirective array," in *IEEE Transactions on Antennas and Propagation*, vol. 30, no. 6, pp. 1172-1176, Nov 1982.

4. E. E. Altshuler, T. H. O'Donnell, A. D. Yaghjian and S. R. Best, "A Monopole Superdirective Array," in *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2653-2661, Aug. 2005.

5. T. H. O'Donnell and A. D. Yaghjian, "Electrically small superdirective arrays using parasitic elements," *2006 IEEE Antennas and Propagation Society International Symposium*, Albuquerque, NM, 2006, pp. 3111-3114.

6. M. Pigeon, A. Sharaiha, and S.Collardey, "Miniature and Superdirective Two Elements Endifre Antenna Array", 8th European Conference on Antennas and Propagation (EuCAP 2014), 6-11 April 2014.

7. A. Haskou, A. Sharaiha and S. Collardey, "Design of Small Parasitic Loaded Superdirective End-Fire Antenna Arrays," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 12, pp. 5456-5464, Dec. 2015.

8. James T. Aberle, Robert Loepsinger-Romak, "Antennas with Non-Foster Matching Networks," in *Antennas with Non-Foster Matching Networks* , 1, Morgan & Claypool, 2007.

9. K. A. Obeidat, B. D. Raines and R. G. Rojas, "Application of Characteristic Modes and Non-Foster Multiport Loading to the Design of Broadband Antennas," in *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 1, pp. 203-207, Jan. 2010.

10. E. A. Elghannai, B. D. Raines and R. G. Rojas, "Multiport Reactive Loading Matching Technique for Wide Band Antenna Applications Using the Theory of Characteristic Modes," in *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 1, pp. 261-268, Jan. 2015.

11. L. Batel, L. Rudant, J. F. Pintos, A. Clemente, C. Delaveaud and K. Mahdjoubi, "High directive compact antenna with non-foster elements," *2015 International Workshop on Antenna Technology (iWAT)*, Seoul, 2015, pp. 381-384.

12. Y. Chen and C. F. Wang, "Synthesis of Reactively Controlled Antenna Arrays Using Characteristic Modes and DE Algorithm," in *IEEE Antennas and Wireless Propagation Letters*, vol. 11, no. , pp. 385-388, 2012

13. J. Mautz and R. Harrington, “Modal analysis of loaded N-port scatterers,” in *IEEE Transactions on Antennas and Propagation*, vol. 21, no. 2, pp. 188-199, Mar 1973.