Biologically Inspired Four Elements Compact Antenna Arrays With Enhanced Sensitivity for Direction of Arrival Estimation

A. Jelodar*, M. Soleimani*, and S. H. Sedighy*(C.A.)

Abstract: A new four elements compact antenna array is presented and discussed to achieve enhanced phase resolution without sacrificing the array output power. This structure inspired by the Ormia Ochracea's coupled ears. The analogy between this insect acute directional hearing capabilities and the electrically compact antenna array is used to enhance the array sensitivity to direction of arrival estimation of an electromagnetic wave. This four elements biomimetic compact array is composed of four strongly coupled antenna elements and two external coupling networks which are designed to enhance the phase resolutions between all antenna element outputs without decrease in the array output power. In other words, this four elements compact array extracts the same power level from the incident EM wave compared with regular array, while the output phase sensitivity is significantly enhanced. The simulation results confirm the advantages of this new compact array compared with the previously reported ones in the literature.

1 Introduction

ANTENNA arrays provide an efficient means to detect and process signals arriving from different directions. Compared with a single antenna that is limited in directivity and bandwidth, a sensor array can modify beam pattern by proper elements amplitude and phase distribution called the array weights [1-3]. In the limited areas, compact arrays with closely antenna elements are unavoidable. In these arrays that the antenna elements are separated by a small distance ($d << \lambda$), there are two main problems: high mutual coupling between elements [4, 5] and low phase sensitivity resolution. The mutual coupling between array elements can be minimized by different techniques such as decoupling networks, metamaterials and EBG structures [6]. For phase sensitivity enhancement, two elements antenna array was introduced in [7-9] to mimic the directional hearing of a small insect behavior named Ormia Ochracea. These two elements antenna arrays achieved enhanced output angular phase resolution by using a passive external coupling network [10]. A two elements antenna array was designed in [11] to obtain a considerably higher output power level compared with the architecture examined in [10]. A three elements biomimetic antenna array has been presented in [12] to provide enhanced phase sensitivity and extract maximum available power from an incoming wave, also. However, the array elements output powers are not efficiently available especially at the boresight angles. A three elements biomimetic antenna array with an electrically small triangular lattice has been proposed in [13] composed of three identical quarter-wavelength-long monopoles to maximize the array phase sensitivity. A generalized model of the biomimetic antenna system was theoretically derived, evaluated, and verified by measurements in [14], also. A method for designing biomimetic array using a non-Foster coupling network was presented in [15] to obtain system stability.

In this paper, a compact four elements biologically inspired antenna array (BIAA) is designed and optimized inspiring from the Ormia Ochracea's coupled ears to enhance the phase angle resolution with efficient output power at all incident angles. In particular, the proposed array enhances the phase resolution while the

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output power level of the antenna array's elements do not become less than the output power of corresponding regular array with the same aperture size and elements at incident wave angle, θ. For this purpose, an upper bound for the phase enhancement factor is presented by modification of the equation presented in [11]. In addition to extending the number of array elements to four in the proposed biologically inspired array, its elements output powers are efficiently available at all incident angles when compared with the references. In other words, the high phase resolution is not achieved at the expense of array elements output power degradation. For demonstration, a four dipole elements antenna array consists of two concatenated passive coupling networks is designed at 800 MHz with $d = \lambda/20$ spacing to achieve phase enhancement factor as $\eta = 3$. Moreover, the output power of elements are similar and only 1% lower than the maximum available power from the array without BIAA's external coupling network at antenna boresight. The simulation results confirm the proposed array design capability and ability to use in compact array direction finding systems, properly.

2 Compact Array

2.1 Principle of Operation

The physically separation between two ears in human and animals help them to detect sound waves of interest and identify and localize their sources. The large enough time difference between the two signals received at ears can be easily used in the central nervous system for direction detection. But, this difference is very small in the insects which have a small head size compared with the sound wavelength. However, the insect capability to hyperacute directional hearing is interesting. For example, Ormia Ochracea is an insect with a remarkable ability to localize an incident acoustic wave source by using a set of mechanically coupled ears rather than two isolated one as shown in Fig. 1 [13]. In other words, Ormia's ears act as a system with two inputs and two outputs where its mechanical system model is depicted in this figure. The analogy
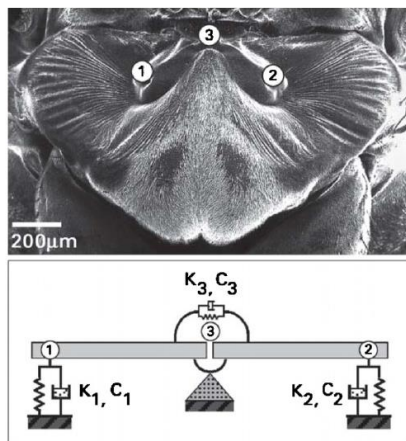
between the hearing mechanism of insects and compact receiving arrays with two antenna elements has been discussed with details in [7].

Based on this analogy, the antenna array can be considered with two excitation modes, common and differential. When the array is excited in the common mode, the two antenna elements are excited with the symmetrical magnitude and zero phase difference, while they are excited in differential mode when the magnitude of excitations are equal but with 180° phase difference. These two excitation modes can be considered in receiving antenna array, also. In this case, the excitation mode is a function of incident EM wave angle as well as spacing between the two elements. Commonly, when an antenna array receives an EM wave with oblique angle of incidence, it is excited with a linear combination of the common and differential modes. In a compact array with closely-spaced elements, the common mode has main contribution in array excitation rather than the differential mode due to the small phase difference between antenna elements. Consequently, such arrays do not have adequate sensitivity to the direction of incoming EM wave [11].
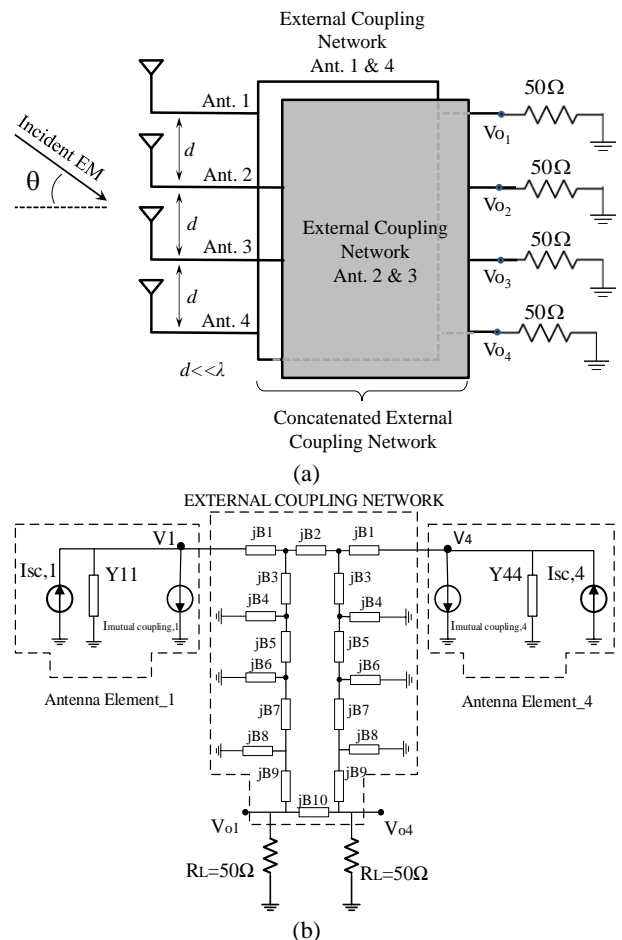

(a)

(b)

Fig. 2 a) Block diagram of the four elements compact antenna array and b) The equivalent circuit model of the proposed network structure shown in part (a) for Ant. 1 and Ant. 4.

Fig. 1 Mechanical model of the Ormia Ochracea's ears [13].

To achieve a compact four elements BIAA, two concatenated passive coupling networks are designed where each pair of antennas are connected to one coupling network to use the common and differential modes of excitation analysis as shown in Fig. 2(a). Due to the array symmetry, both 1 and 4 antenna elements, as well as 2 and 3 ones, connect to separate coupling network as shown in the figure. Note that the mutual coupling of two elements that are not connected should be considered in the equivalent circuit models. The equivalent circuit model of this network is shown in Fig. 2(b). The four antennas in the array are considered similar which are separated by distance of $d = \lambda/20 << \lambda$ from each other. The antenna element current can be expressed with mutual coupling effect of other elements as

$$I_{MutualCoupling,1} = Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \tag{1a}$$

$$I_{MutualCoupling,2} = Y_{21}V_1 + Y_{23}V_3 + Y_{24}V_4 \tag{1b}$$

$$I_{MutualCoupling,3} = Y_{31}V_1 + Y_{32}V_2 + Y_{34}V_4 \tag{1c}$$

$$I_{MutualCoupling,4} = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 \tag{1d}$$

where Y_{ij} are the entries of the antenna admittance matrix.

2.2 Design and Formulation

The two proposed concatenated coupling networks are symmetric and consist of reactances, B_1–B_{10} (B'_1–B'_{10}). Notice that the prime notation is used for the network connected 2 and 3 elements. Each coupling networks are placed between a pair of antennas and connected to two constant load impedances $R_L = 50\Omega$.

The short circuit current magnitudes of the four elements in the compact array are shown in Fig. 3. The elements are dipole antennas with 17.8cm length and separated by 18.75mm. These results are obtained in different incident angles (θ) from CST full-wave simulation software, at 800MHz. As expected, the antenna elements show a symmetrical behavior respect to θ.
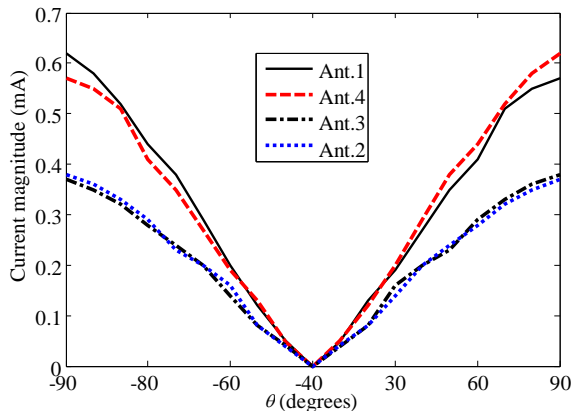

Fig. 3 Magnitudes of the short-circuit currents of four 17.8cm long monopole antennas spaced at a distance of 18.75cm operating at 800MHz frequency.

Figure 4(a) shows the equivalent circuit model of the compact array in common mode excitation, where $I_{mutualCoupling1,4}$ is the mutual coupling between 1th and 4th elements. Also, the equivalent circuit model in differential excitation mode is shown in Fig. 4 (b).

$$I_{MutualCoupling,1,4} = Y_{12}V_2 + Y_{13}V_3 \tag{2a}$$

$$I_{MutualCoupling,2,3} = Y_{21}V_1 + Y_{24}V_4 \tag{2b}$$

Referring to Fig. 4, the common and differential modes (I_d and I_c) short circuit currents can be calculated as

$$I_{c1,4} = \frac{I_{sc,1} + I_{sc,4}}{2} \tag{1a}$$

$$I_{c2,3} = \frac{I_{sc,2} + I_{sc,3}}{2} \tag{1b}$$

$$I_{d1,4} = \frac{I_{sc,4} - I_{sc,1}}{2} \tag{1c}$$

$$I_{d1,4} = \frac{I_{sc,3} - I_{sc,2}}{2} \tag{1d}$$

Next, we derive a new expression for the phase enhancement factor of the compact array at arbitrary angles of incident wave (θ), and determine a theoretical upper bound for its amount by equation modification presented in [11]. The phase enhancement factor can be defined as $\eta(\theta_0) = S/S_{\theta0}$ where $S_{\theta0}$ is the output phase derivative of the regular array (compact array without coupling network) respect to the angle of incident wave at θ_0

$$S_{\theta_0} = \frac{d(\frac{2\pi d}{\lambda}\sin\theta)}{d\theta}\bigg|_{\theta=\theta_0} = \frac{2\pi d}{\lambda}\cos\theta_0 \tag{4}$$

and S is output phase difference derivative $\Phi_{out} = \angle V_{o4} - \angle V_{o1}$ in the compact array as

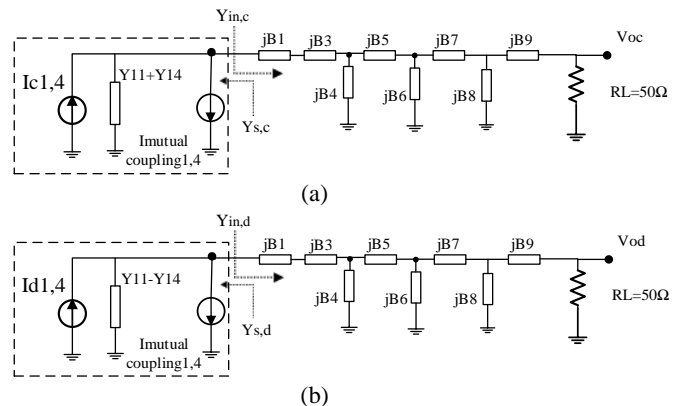$$S = \frac{d\phi_{out}}{d\theta}\bigg|_{\theta=\theta_0} \tag{5}$$

Fig. 4 The equivalent circuit models of the four element compact antenna array shown in Fig. 2 (b) for a) common and b) differential mode excitation.

Also, we have

$$S = 2\frac{d}{d\theta_0}\left(\left|\frac{V_{od}}{V_{oc}}\right|\sin\varphi\right) \quad (6)$$

where

$$\varphi = \angle V_{od} - \angle V_{oc} \quad (7)$$

Referring to [11], compact array design with the same output power as a regular array and similar elements, the load impedance (50Ω) should be matched to the antenna array admittance in common mode by design of coupling network as

$$Y_{s,c} = Y_{in,c}^* \quad (8)$$

Antenna matching in common mode results in the maximum magnitude of the output voltage which can be written as

$$\left|V_{oc}^{\max}\right| = \frac{1}{2}\left|I_{c1,4}(\theta)\right|\sqrt{\frac{1}{G_cG_L}} \quad (9)$$

where G_c and G_L are the common mode and load conductance, respectively. According to [11], the differential mode output voltages should be maximum to achieve maximum phase enhancement factor. Therefore, the maximum magnitude of the output differential mode voltage at θ_0 can be written as

$$\left|V_{od}^{\max}\right| = \frac{1}{2}\left|I_{d1,4}(\theta)\right|\sqrt{\frac{1}{G_cG_L}} \quad (10)$$

where $G_{s,c} = \mathrm{real}\{Y_{s,c}\}$ and $G_{s,d} = \mathrm{real}\{Y_{s,d}\}$. The values of $G_{s,c}$ and $G_{s,d}$ can be achieved by matching the array in common and differential excitation mode. The parameters $G_{s,c}$ and $G_{s,d}$ in the compact array for two pairs of antennas (2 and 3) and (1 and 4) are obtained by simulation and presented in Table 1. Also, the values of $f(\theta)$ can be determined by evaluating the short circuit current phase of the antenna elements.

After evaluating $G_{s,c}$ and $G_{s,d}$ and the short circuit currents of the antenna elements, we can determine the upper bound of the phase enhancement factor in each angle θ as listed in Table 2.

Here, we want to achieve $\eta = 3$ for each angle of incident wave, θ. For this purpose, the external coupling network parameters $B_1–B_{10}$ and $B_1'–B_{10}'$ should be optimized by applying five goals based on the five

Table 1 Calculated conductance parameters of the four dipole antenna system at 800MHz.

$G_{s,c,1,4}$	22.14 m℧
$G_{s,d,1,4}$	1.85 m℧
$G_{s,c,2,3}$	8.76 m℧
$G_{s,d,2,3}$	4.21 m℧

Table 2 The phase enhancement factor values between two pair of antenna elements, 1 & 4 and 2 & 3 versus incident angles, θ.

$\theta°$	10	20	30	40	50
$\eta_{1,4}^{\max}$	3.6	4.14	4.94	5.86	7.33
$\eta_{2,3}^{\max}$	4.75	5.47	6.41	7.75	9.79
$\theta°$	60	70	80	90	
$\eta_{1,4}^{\max}$	9.7	14.47	28.92	∞	
$\eta_{2,3}^{\max}$	13.21	20.08	40.1	∞	

Table 3 The problem optimization goals.

Phase goals	Power goals
$\angle V_{o1} = \eta/2 \times kd_{1,4}\sin\theta$	
$\angle V_{o2} = \eta/2 \times kd_{2,3}\sin\theta$	
$\angle V_{o3} = \eta/2 \times kd_{2,3}\sin\theta$	$P_{\mathrm{out,couplingNetwork}} = P_{\mathrm{out,RegularNetwork}}$
$\angle V_{o4} = \eta/2 \times kd_{1,4}\sin\theta$	

nonlinear equations on output ports of the coupling network, phases and power as shown in Table 3.

The distance between antenna 2 and 3 is $d_{2,3} = \lambda/20$ where $d_{1,4} = 3\lambda/20$ is the distance between antenna 1 and 4. By satisfying the above-mentioned goals, $\eta = 3$ can be achieved for all output phases of the four antenna elements in the compact array.

3 Results and Discussion

To consider the practicality implementation conditions, the inductor elements are considered in the simulation as non-ideal and lossy reactive elements with $Q = 50$. Moreover, the transmission line with 50Ω characteristic impedance and length of 4mm placed in series with each component for connection. The component values for two external coupling network are obtained from the optimization procedures done by ADS simulation software as tabulated in Table 4.

Figure 5 shows the simulated output phase responses of the compact array with respect to the angle of radiation θ, and compares these results with the desired output phase of the array achieving $\eta = 3$. As can be seen, the output phase of each antenna approximately matches its desired output phase and therefore the output phase difference between all four antennas in the proposed compact array are enhanced. Moreover, Fig. 6 depicts the phase enhancement factor values between all of the antenna elements.

As expected, the phase enhancement factors for all antenna elements are about 3 where the slight variance of η is due to the slight deviation of the output phase of the antenna elements from optimum values. The simulated power levels at the four antenna elements outputs normalized respect to the output power of the regular array (antenna array without coupling network) are shown in Fig. 7 versus θ. As can be seen, the compact array output power is approximately similar to the regular array. Moreover, as the angle of wave
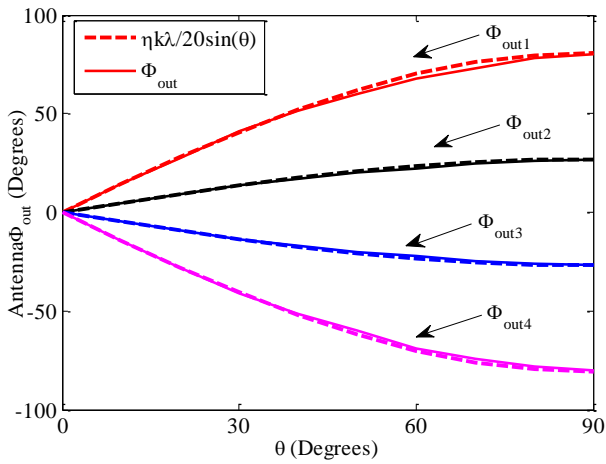
Fig. 5 Simulated output phase responses of the four elements compact array discussed in Section 2
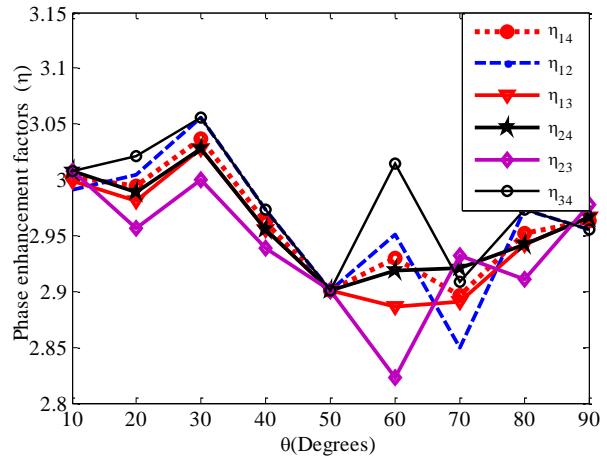

Fig. 6 Phase enhancement factor of the compact array between all antenna elements versus incident angle of, θ.

Fig. 7 Simulated output power of the four elements compact array.

Table 4. Values for the external coupling network components (in m℧) obtained from the optimization process.

Component	B [℧]	L or C	B' [℧]	L' or C'
1	3.156	628 pF	0.31	628 pH
2	0.014	13.6 nH	0.89	177 pF
3	0.83 m	239 nH	41.4 μ	4.8 μH
4	0.032	6.53 pF	8.545	1.7 nF
5	0.0035	706 fF	0.56 m	350 nH
6	0.234	46.6 pF	0.786	253 pH
7	0.138	1.44 nH	35 μ	5.68 uH
8	0.049	9.86 pF	0.32	63.68 pF
9	0.0031	618 fF	0.2	973 nH
10	20.8 μ	9.53 uH	31.4μ	6.32 uH

incident increases and becomes closer to 90°, the array output power is more close to the regular array output power.

4 Conclusion

A new architecture for four elements compact antenna array was presented and discussed to enhance the phase resolution. A theoretic upper bound for the phase enhancement factor was obtained versus θ which guarantees that the array output power is similar to the similar regular array. The four dipole elements antenna array which is consists of two concatenated passive coupling networks was designed at 800MHz with $d = \lambda/20$ spacing to achieve phase enhancement factor as $\eta = 3$. The simulation results verified that the array output power at each element is similar and only 1% lower than the maximum available power from the antenna array without the BIAA's external coupling network at antenna boresight. Therefore, the proposed array can be used in compact array direction finding systems, efficiently.

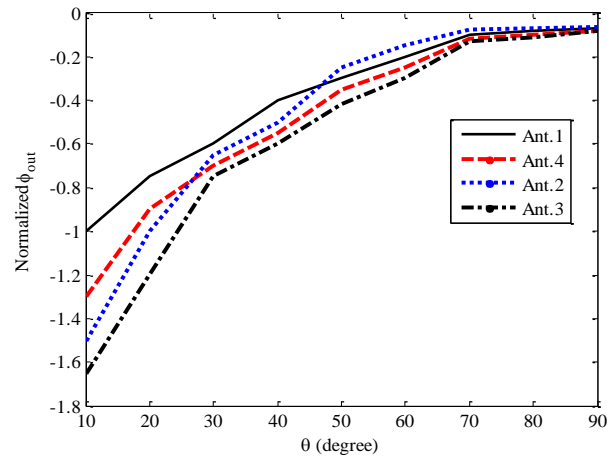## Appendix

As discussed, the derivative of the output phase difference of the compact array as

$$S = \frac{d\,\Phi_{out}}{d\,\theta}\bigg|_{\theta=\theta_0} = \frac{d\left(\angle V_{O2} - \angle V_{O1}\right)}{d\,\theta}\bigg|_{\theta=\theta_0}$$

$$= \frac{d}{d\,\theta}\left(\angle\left\{\frac{1+\dfrac{V_{od}}{V_{oc}}}{1-\dfrac{V_{od}}{V_{oc}}}\right\}\right)\Bigg|_{\theta=\theta_0}$$

$$= \frac{d}{d\,\theta}\left(\angle\left\{\frac{1+\mathrm{Re}\left\{\dfrac{V_{od}}{V_{oc}}\right\}+j\,\mathrm{Im}\left\{\dfrac{V_{od}}{V_{oc}}\right\}}{1-\mathrm{Re}\left\{\dfrac{V_{od}}{V_{oc}}\right\}-j\,\mathrm{Im}\left\{\dfrac{V_{od}}{V_{oc}}\right\}}\right\}\right)\Bigg|_{\theta=\theta_0}$$

$$= \frac{d}{d\,\theta}\left(2\times\mathrm{Im}\left\{\frac{V_{od}}{V_{oc}}\right\}\right)\Bigg|_{\theta=\theta_0}$$

$$= \frac{d}{d\,\theta}\left(2\times\left|\frac{V_{od}}{V_{oc}}\right|\sin\left(\varphi\right)\right)\Bigg|_{\theta=\theta_0} \tag{12}$$

where $\varphi = \angle V_{od} - \angle V_{oc}$. Also, we have

$$\left|V_{oc}^{\max}\right| = \frac{1}{2}\left|I_{c1,4}(\theta)\right|\sqrt{\frac{1}{G_c G_L}} \qquad (13)$$

$$\left|V_{od}^{\max}\right| = \frac{1}{2}\left|I_{d1,4}(\theta)\right|\sqrt{\frac{1}{G_d G_L}} \qquad (14)$$

Assuming $\varphi = 90°$, $I_{sc,1} = A(\theta)e^{jf(\theta)}$, and $I_{sc,4} = A(\theta)e^{-jf(\theta)}$, $|I_{c1,4}(\theta)|$, and $|I_{d1,4}(\theta)|$ can be written as:

$$\left|I_{c1,4}\right| = \left|\frac{I_{sc,1} + I_{sc,4}}{2}\right| = A(\theta)\left|\cos(f(\theta))\right| \qquad (15)$$

$$\left|I_{d1,4}\right| = \left|\frac{I_{sc,4} - I_{sc,1}}{2}\right| = A(\theta)\left|\sin(f(\theta))\right| \qquad (16)$$

Therefore, S can be expressed as

$$S = 2\frac{d}{d\theta}\left(\left|\tan(f(\theta))\right|\sqrt{\frac{G_c}{G_d}}\right) \qquad (17)$$

The maximum phase enhancement factor to have the same output powers (similar to a regular array) can be written as

$$\eta^{\max}(\theta) = \frac{\lambda}{\pi d \cos\theta}\frac{d}{d\theta}\left(\left|\tan f(\theta)\right|\right)\sqrt{\frac{G_{s,c}}{G_{s,d}}} \qquad (18)$$

where $G_{s,c} = \text{real}\{Y_{s,c}\}$ and $G_{s,d} = \text{real}\{Y_{s,d}\}$.

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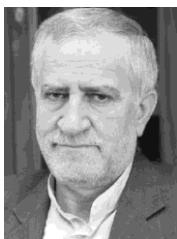
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