INTERCEPT POINTS OF ACTIVE PHASED ARRAY ANTENNAS

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ABSTRACT

We derive an equation for the Nth order intercept point of an active phased array antenna with an amplitude taper. The antenna utilizes a T/R module to control the phase and amplitude of each array element. As an example, we show the effect of various levels of Taylor weighting on the 3rd order intercept point of a large phased array.

INTRODUCTION

Active phased array antennas which employ a solid-state transmit/receive (T/R) module to control each element provide the ultimate electrical performance for radar systems. In large part, the transmit and receive performance of a phased array is determined by the performance of the individual T/R module. On receive, the module's gain, noise figure and third-order intercept (TOI) set the antenna's output intercept point and system noise figure. In addition, the T/R module usually contains a phase shifter and variable gain amplifier to steer the beam and weight the aperture distribution on receive.

Since the T/R module contains devices which have nonlinear characteristics, its intercept points are critical in setting the antenna's intercept points. In particular, we are interested most often in the module's TOI, because the third-order spurs often fall within the antenna and signal processor's passbands.

The receive analysis of the phased array is complicated by the fact that it is a multiport network with many inputs and one output, and the standard intercept point analysis applies to two-port networks [1]. When the receive aperture distribution is uniform, all paths through the antenna have the same insertion and intercept characteristics. We simply obtain the antenna output intercept point by multiplying the output intercept point of the T/R module by the number of elements and subtracting any beamformer insertion losses.

For most radar applications, very low receive side lobes are desired to reduce the levels of clutter, jammers and other spurious signals compared to the level of the target return. Lee has already derived expressions for the effective noise figure of the array when a low side lobe amplitude taper is applied across the array aperture [2]. In this paper we derive an equation for the effective nth order output intercept point

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of an active phased array when an amplitude taper is applied. Then, we simplify the equation to give the third-order intercept, and show the effect of a Taylor amplitude taper on the TOI of a large phased array.

THEORY

Figure 1 shows a block diagram of a simplified phased array with M identical T/R modules. We assume that all the T/R module outputs are combined in a single, lossless, M:1 combiner. The combiner has voltage coupling coefficients, $C_i = 1/\sqrt{M}$. We model the ith T/R module by a single amplifier with maximum gain G_{max} and weighted gain $G_i = G_{max} w_i^2$ where w_i is the voltage excitation determined from the low side lobe taper. We assume a main beam directed at broadside, so w_i is pure-real valued; however, our result is independent of the direction of the main beam. The nth order output intercept point of the ith module is given by $I_{i,o,n}$ and may be a function of G_i. We will derive an equation for $I_{a,n}$, the effective, nth order, output intercept point of the antenna shown in the figure.

Two signals, V_1 and V_2, are incident on each element of the array. The signals are given by:

$$V_1 = \frac{1}{\sqrt{2}} \cos \omega_1 t \qquad V_2 = \frac{1}{\sqrt{2}} \cos \omega_2 t$$

If the frequencies are approximately equal, then $V_1 = V_2 = V = \frac{1}{\sqrt{2}} \cos \omega t$. For a two-port, the equation relating the power in the nth order harmonic to that in the signal is

$$P_{a,n}^{dB} = n P_{a,1}^{dB} - (n-1) I_{a,n}^{dB} \qquad (1)$$

where the dB superscript means the quantities are in decibels, and the subscript a,n denotes the antenna output, nth order harmonic. To solve for $I_{a,n}$ is straightforward:

$$I_{a,n} = \frac{(P_{a,1})^{\frac{n}{n-1}}}{(P_{a,n})^{\frac{1}{n-1}}} \qquad (2)$$

where the quantities are in Watts. From equation (2), we can determine $I_{a,n}$ from the 1st (signal) and nth harmonic antenna power outputs. The signal power out of the antenna is given by

$$P_{a,1} = \left(\sum_{i=1}^{M} \sqrt{G_i} C_i \right)^2 = \frac{G_{max}}{M} \left(\sum_{i=1}^{M} w_i \right)^2 \qquad (3)$$

From equation (2) we see that the nth harmonic power output from the ith T/R module will take the form:

$$P_{i,n} = \frac{(P_{i,1})^n}{I_{i,o,n}^{n-1}} \qquad (4)$$

We solve for the nth harmonic voltage by taking the square root of equation (4) and noting that $P_{i,1} = 2V^2 G_i = G_i = G_{max} w_i^2$:

$$V_{i,n} = \frac{(G_{max} w_i^2)^{n/2}}{I_{i,o,n}^{(n-1)/2}} \qquad (5)$$

The nth harmonic power at the output of the antenna is given by

$$\begin{aligned} P_{a,n} &= \left(\sum_{i=1}^{M} V_{i,n} C_i \right)^2 = \frac{1}{M} \left[\sum_{i=1}^{M} \frac{(G_{max} w_i^2)^{n/2}}{I_{i,o,n}^{(n-1)/2}} \right]^2 \\ &= \frac{G_{max}^n}{M} \left(\sum_{i=1}^{M} \frac{w_i^n}{I_{i,o,n}^{(n-1)/2}} \right)^2 \end{aligned} \qquad (6)$$

If we substitute equations (3) and (6) into equation (2), we obtain the desired equation for the nth order antenna output intercept:

$$I_{a,n} = \frac{1}{M}\left[\frac{\left(\sum_{i=1}^{M} w_i\right)^{2n}}{\left(\sum_{i=1}^{M} \frac{w_i^n}{I_{i,o,n}^{(n-1)/2}}\right)^2}\right]^{\frac{1}{n-1}} \quad (7)$$

For uniform weighting (all $w_i = 1$), we get the maximum antenna intercept point, $I_{a,n} = I_{o,n}M$, where $I_{o,n}$ is the module intercept for $G_i = G_{max}$. If we divide equation (7) by $I_{o,n}M$, we get the antenna output intercept point normalized to the intercept point for uniform excitation:

$$\overline{I_{a,n}} = \frac{1}{M^2 \cdot I_{o,n}}\left[\frac{\left(\sum_{i=1}^{M} w_i\right)^{2n}}{\left(\sum_{i=1}^{M} \frac{w_i^n}{I_{i,o,n}^{(n-1)/2}}\right)^2}\right]^{\frac{1}{n-1}} \quad (8)$$

For the third order intercept point, equation (8) becomes

$$\overline{I_{a,3}} = \frac{1}{M^2 \cdot I_{o,3}} \frac{\left(\sum_{i=1}^{M} w_i\right)^3}{\left(\sum_{i=1}^{M} \frac{w_i^3}{I_{i,o,3}}\right)} \quad (9)$$

Two specific cases which bound the result of equation (9) are (1) when the *output* intercept point of the T/R module is independent of G_i, that is the last stage of the T/R module sets its intercept point, and (2) when the *input* intercept point of the module is independent of G_i. For case (1), $I_{i,o,3} = I_{o,3}$ and equation (9) becomes

$$\overline{I_{a,3}} = \frac{1}{M^2} \frac{\left(\sum_{i=1}^{M} w_i\right)^3}{\left(\sum_{i=1}^{M} w_i^3\right)} \quad (10)$$

For case (2), $I_{i,o,3} = G_i I_3 = G_{max} w_i^2 I_3$ where I_3 is the module's input intercept point, and equation (9) becomes

$$\overline{I_{a,3}} = \left(\frac{\sum_{i=1}^{M} w_i}{M}\right)^2 \quad (11)$$

which is equivalent to the loss in signal relative to that of a uniform taper through the array.

Note, that the above analysis applies to signals in the direction of the sum beam only, i.e., we assume that all signals incident on the array are in phase.

DISCUSSION

Figure 2 shows a plot of the antenna output, third-order intercept versus Taylor design side lobe level for a rectangular array of 16,384 elements. The element lattice is triangular, with spacings $d_x = 0.54\lambda$ and $d_y = 0.30\lambda$, and the array is 69 wavelengths wide by 72 wavelengths high. We apply the same Taylor linear taper parameters along the height and width of the array. We calculated the normalized antenna, third-order intercept point using equations (10) and (11). The degradation in the intercept point becomes quite significant for low side lobe levels. Clearly, the taper reduces the antenna's output intercept point just like an attenuator placed after an amplifier.

References

[1] S. A. Maas, *Nonlinear Microwave Circuits* Norwood, MA: Artech House, 1988.

[2] J. J. Lee, "G/T and Noise Figure of Active Array Antennas," *IEEE Trans. Antennas and Propagat.*, vol. 41, no. 2, February 1993, pp. 241-244.

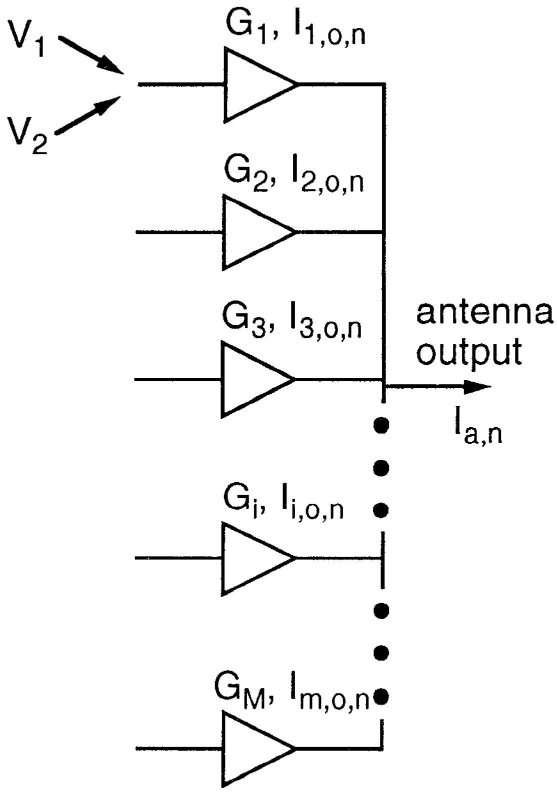

Figure 1: M-element phased array block diagram.

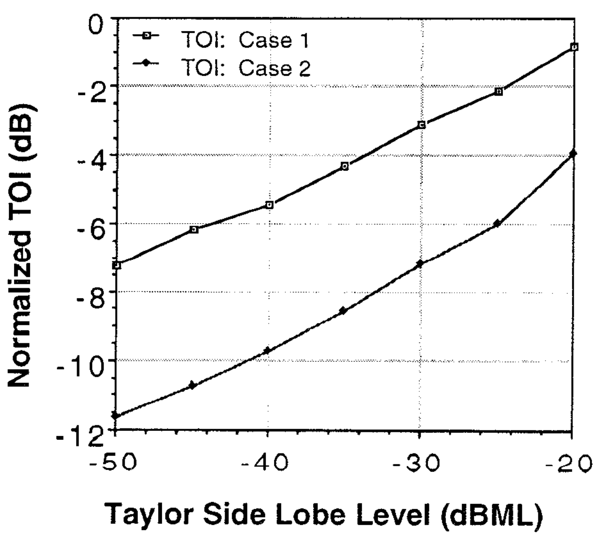

Figure 2: Antenna output TOI relative to uniform weighting. 16,384 elements, rectangular aperture, triangular lattice (dx=0.54 λ, dy=0.30 λ). nbar=6 for SLL up to -25 dB; otherwise nbar=12.