Adaptive Arrays

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(Invited Paper)

Abstract– This paper presents some types of adaptive antennas and the historical development of adaptive antennas. It explains some of the common algorithms associated with digital beamforming then presents techniques for adaptation using conventional arrays with corporate feeds, including the use of reconfigurable antenna elements.

Index terms– adaptive antenna, adaptive nulling, genetic algorithms reconfigurable antenna.

I. TYPES OF ADAPTIVE ANTENNAS

An adaptive antenna is an antenna that modifies its receive or transmit characteristics in order to enhance the antenna's performance. The antenna alters its performance in order to respond to environmental or operational changes. Adaptive antennas rely upon signal processing and/or artificial intelligence algorithms to make changes or adapt. "Smart" and "Adaptive" are often used interchangeably.

Some types of adaptive antennas and how they work include:

1. Beam switching selects the beam that best receives the desired signal. Fig. **1** shows an array with a Rotman lens [1] feed. Only beams pointing in the directions of sources receive a signal. The beams can be switched as the signal environment changes.

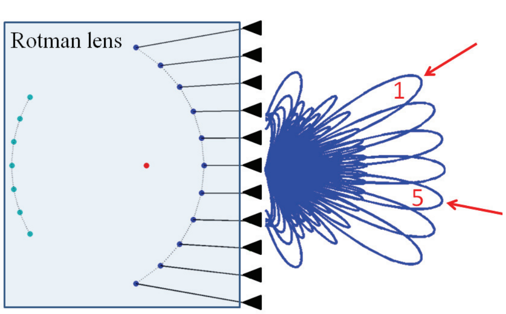

Fig. 1. Rotman lens with multiple beams.

2. Direction finding automatically detects signals and places nulls in the directions of those signals. An algorithm determines where those nulls are and hence the location of the signals. An Adcock array [2] was developed about 100 years ago. It finds the signal direction by calculating the ratio of the difference to sum patterns. Fig. **2** shows the sum and difference patterns associated with a four element Adcock array.

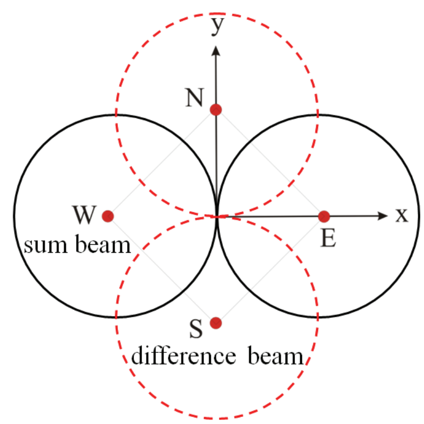

Fig. 2. Diagram of an Adcock array.

3. Retrodirective arrays retransmit a received signal in a desired direction, usually the direction of the incident signal. The retrodirective array in Fig. **3** receives a signal, takes the complex conjugate (and possibly amplifies it), then retransmits it.
4. MIMO (multiple input multiple output) has arrays at the transmit and receive ends of a communications system (Fig. **4**). The signals at each element are weighted such that the desired signal is received in a high multipath environment. The channel path is characterized between each element (h_{mn}) and placed in a channel matrix. The transmitted data is found by inverting the channel matrix

and multiplying the received data. The arrays must be continuously calibrated in order to have accurate values of h_{mn}.

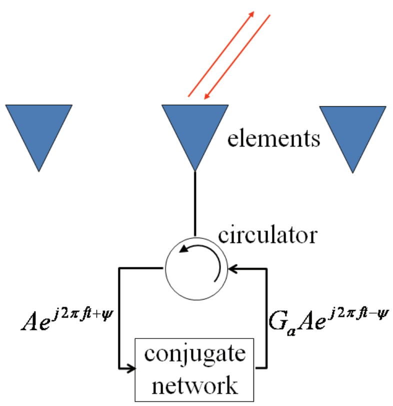

Fig. 3. Diagram of a retrodirective array.

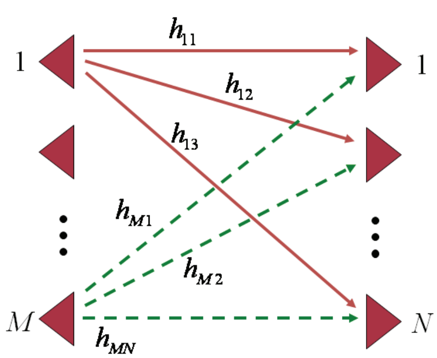

Fig. 4. MIMO concept.

5. Reconfigurable antennas alter their physical properties (usually through some type of switch) in order to change their resonant frequency or polarization. The main patch in Fig. **5** is resonant at f_0. Closing the switches increases the size of the patch and makes it resonant at a new frequency that is lower than f_0.

Fig. 5. Reconfigurable patch antenna.

6. Adaptive nulling places a null in the direction of interfering signals while maintaining sufficient gain in the direction of the desired signal to receive it. If an interference signal enters a sidelobe (dashed line in Fig. **6**), then the adaptive algorithm finds array weights that place a null in the direction of the interference (solid line in Fig. **6**).

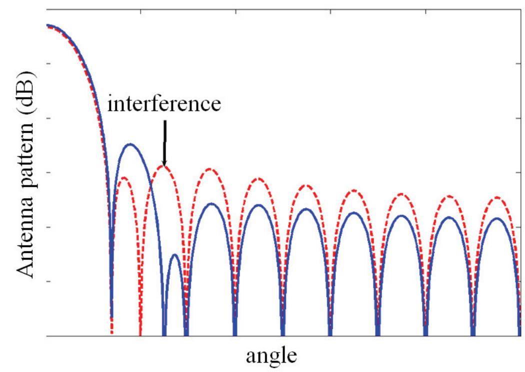

Fig. 6. Adaptive nulling places a null in the sidelobe where interference is present.

The next section describes the historical development of adaptive antennas along with a brief summary of some of the popular algorithms. The antenna architecture of choice is the digital beamforming array. An alternative is to use a more conventional corporate fed array with hardware signal weights at the elements. Some hardware and software developments for this approach are also presented. This paper is based upon the plenary talk given at the 2009 ACES Conference [1].

II. HISTORICAL DEVELOPMENT

Antenna arrays are necessary for implementation of almost all adaptive antenna ideas. Direction finding had a giant leap forward when Adcock used four monopole antennas placed on the edges of a square, and Watson-Watt [3] developed the simple trigonometric formula for finding the elevation and azimuth of a source incident on an Adcock array.

Scanning an array by changing the phase of the signals to the elements in the array was first tried by Braun [4]. Other antenna array developments centered upon developing low sidelobe amplitude tapers for linear arrays. Starting with the impractical binomial taper [5] then progressing to the more practical Dolph-

Chebychev [6] and further to the useful Taylor amplitude taper [7]. Along the way, Schelkunoff [8] outlined the use of the z-transform for general synthesis of antenna patterns.

Ideas for actual "adaptive" antennas did not originate until the 1950's. The Van Atta array reflects an incident wave in a predetermined direction with respect to the incident angle [9]. Usually, this type of retrodirective array amplifies and phase shifts the receive signal such that it retransmits in the direction of the incident field.

Beam switching is based upon the idea that multiple beams are formed by the array and the beam that best receives the desired signal is selected. Multiple beams are possible through feed networks like the Butler matrix and the Rotman lens . Both approaches have orthogonal beams that can cover a wide area. Beam switching steers a high gain beam in the direction of the desired signal but does nothing to mitigate interference entering the sidelobes.

An antenna array has many signals incident on it as shown in Fig. 7. The goal of a direction finding array is to place nulls in the directions of all signals by adjusting the weighting at each element then calculate the location of the nulls from the resultant weights. Adaptive nulling is similar, except it does not want to place a null in the direction of the desired received signal. The signal processing algorithms used for direction finding and adaptive nulling are similar and based upon knowing the amplitude and phase of the signals received at each element in the array.

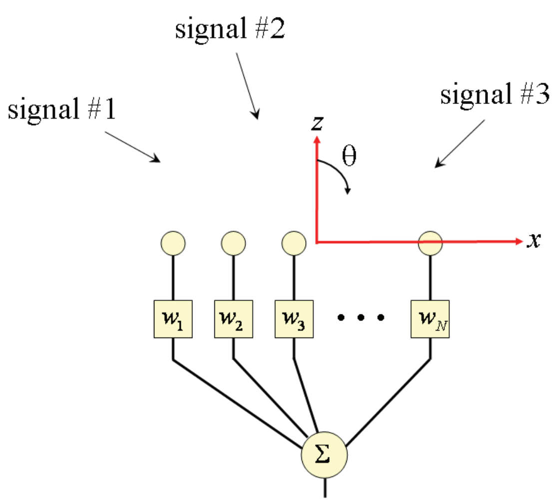

Fig. 7. Diagram of an antenna array with weights at each element.

The first adaptive nulling array was sidelobe canceller developed in the late 1950's by Howells and Applebaum [11]. A sidelobe canceller has a high gain antenna for receiving the desired signal accompanied by one or more small low gain, broad beam antennas for sidelobe cancellation (Fig. **8**). The low gain antenna amplifies the jamming and desired signals the same, since it is omnidirectional. Appropriately weighting and subtracting the low gain antenna signal from the high gain antenna signal cancels the interference. Applying this concept to every element in an array resulted in a fully adaptive array [12].

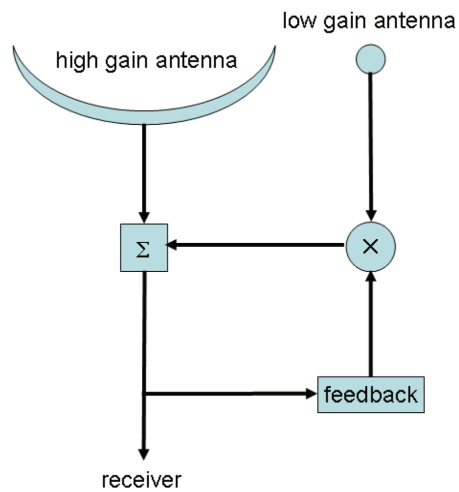

Fig. 8. Single Howells-Applebaum loop for a sidelobe canceller.

Almost all adaptive nulling algorithms are based upon the Wiener-Hopf solution [13] which gives the optimum weights at the elements in the array.

$$\mathbf{w}_{opt}(\kappa) = \mathbf{R}^{-1}(\kappa) E\left[\mathbf{d}(\kappa)\mathbf{s}(\kappa)\right] \qquad (1)$$

where

$\mathbf{R}$ = signal covariance matrix
$\mathbf{d}$ = desired signal
$\mathbf{s}$ = signal vector
κ = time step
$E[\ ]$ = expected value operator

In the 1960's the least mean square (LMS) algorithm was developed [14] and became the standard. Most adaptive algorithms started with hardware implementations, because computer resources were limited. A variety of algorithms have been developed over the past 40 years, many based upon the LMS algorithm given by

$$\mathbf{w}(\kappa+1)=\mathbf{w}(\kappa)+\mu\mathbf{s}(\kappa)\left[\mathbf{d}(\kappa)-\mathbf{w}^{\dagger}\mathbf{s}(\kappa)\right] \quad (2)$$

where μ is the step size. Other well-known algorithms, such as recursive least squares and constant modulus, use various techniques for approximating the inverse signal covariance matrix in (1).

III. DIGITAL BEAMFORMING

The signal covariance matrix is easily formed when every element in the array has a receiver. Ideally, placing an analog-to-digital (AD) converter at each element in the array feeds a digital signal to the computer where all the beamforming and beam steering is done. Adaptively switching beams as well as placing nulls in sidelobe becomes relatively easy with a digital beamformer. Unfortunately, calibrating the hardware and developing the hardware necessary to do the processing is difficult and expensive. AD converters are limited to frequencies in the low GHz range. The next two sections describe some DF and adaptive nulling algorithms that use a digital beamformer.

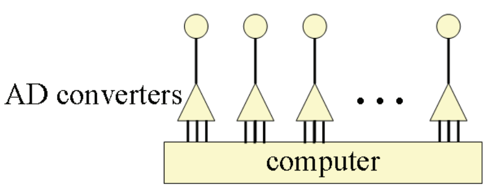

Fig. 9. Digital beamforming array.

IV. DIRECTION FINDING

Direction finding is accomplished by either pointing the main beam or pointing nulls at N_s sources. The relative array output power as a function of angle can be found by

$$P(\theta)=A^{\dagger}(\theta)R_T A(\theta) \quad (3)$$

where the uniform array steering vector is given by

$$A(\theta)=e^{jkx_n\cos\theta}, \theta_{\min}\le\theta\le\theta_{\max}. \quad (4)$$

A plot of the output power vs. angle is known as a periodogram. This spectrum is basically the output from steering the main beam between $\theta_{\min}$ and $\theta_{\max}$. Resolving closely spaced signals is limited by the array beamwidth.

The signal-to-interference ratio at the array output is maximized by the following array weights:

$$w=\frac{R_T^{-1}A}{A^{\dagger}R_T^{-1}A} \quad (5)$$

The resulting Capon spectrum [15] is given by

$$P(\theta)=\frac{1}{A^{\dagger}(\theta)R_T^{-1}A(\theta)}. \quad (6)$$

The (MUSIC) [16] *MU*ltiple *SI*gnal *C*lassification spectrum is given by

$$P(\theta)=\frac{A^{\dagger}(\theta)A(\theta)}{A^{\dagger}(\theta)V_\lambda V_\lambda^{\dagger}A(\theta)} \quad (7)$$

where V_λ is a matrix whose columns contain the eigenvectors of the noise subspace. The eigenvectors of the noise subspace correspond to the $N-N_s$ smallest eigenvalues of the correlation matrix. The denominator of (7) can be written as

$$A^{\dagger}(\theta)V_\lambda V_\lambda^{\dagger}A(\theta)=\sum_{n=M+1}^{M-1}c_n z^n \quad (8)$$

where

$z=e^{jknd\sin\theta}$

$c_n=\sum_{r-c=n}V_\lambda V_\lambda^{\dagger}$ =sum of nth diagonal of $V_\lambda V_\lambda^{\dagger}$

Solving for the angle of the phase of the roots of the polynomial in (8) produces

$$\theta_m=\sin^{-1}\left(\frac{\arg(z_m)}{kd}\right). \quad (9)$$

The maximum entropy method (MEM) spectrum is given by [18]

$$P(\theta)=\frac{1}{A^{\dagger}(\theta)R_T^{-1}[:,n]R_T^{\dagger-1}[:,n]A(\theta)} \quad (10)$$

where n is the n$^{\text{th}}$ column of the inverse correlation matrix.

To demonstrate the capabilities of these algorithms, consider an 8 element array of isotropic point sources spaced $\lambda/2$ apart and lying along the x-axis. Sources are incident on the array at -60^o, 0^o, and 10^o with relative powers of 0, 4, and 12 dB, respectively. The periodogram has broad peaks and cannot distinguish the sources at 0^o and 10^o. Capon, MUSIC, and MEM spectra have very sharp spikes in the directions of the sources and can distinguish closely spaced sources.

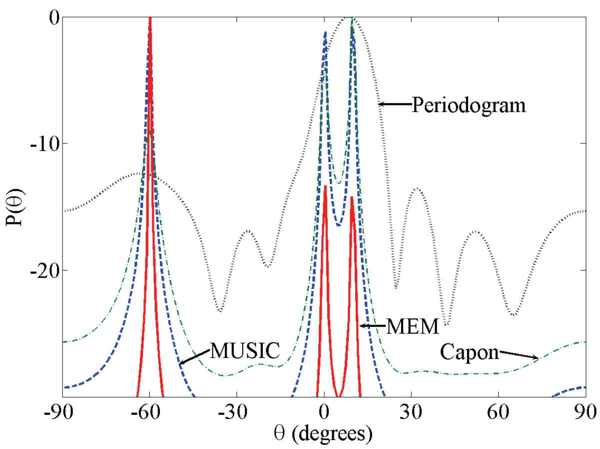

Fig. 10. Plot of the direction finding spectra for an 8 element array.

V. ADAPTIVE NULLING

In practice, the correlation matrix is estimated by a sample matrix, $\hat{R}_T$. This estimate can be formed using K samples of the received element signals

$$R_T = \frac{1}{K}\sum_{\kappa=1}^{K} x(\kappa)x^{\dagger}(\kappa) \tag{11}$$

and the correlation vector is

$$\mathbf{q}(\kappa) = \frac{1}{K}\sum_{\kappa=1}^{K} d^{\dagger}(\kappa)\mathbf{s}(\kappa). \tag{12}$$

This approach is known as sample matrix inversion (SMI) [18]. At the kth time sample, the SMI weights are given by

$$w(\kappa) = R_T^{-1}(\kappa)q(\kappa). \tag{13}$$

The recursive least squares (RLS) algorithm [19] recursively updates the correlation matrix such that more recent time samples receive a higher weighting than past samples. A straight-forward implementation of the algorithm is written as

$$R_T(\kappa) = x(\kappa)x^{\dagger}(\kappa) + \alpha R_T(\kappa-1) \tag{14}$$

and the correlation vector is

$$\mathbf{q}(\kappa) = d^{\dagger}(\kappa)\mathbf{s}(\kappa) + \alpha q(\kappa-1) \tag{15}$$

where the forgetting factor, α, is limited by $0 \le \alpha \le 1$.

To demonstrate the capabilities of these algorithms, consider an 8 element array of isotropic point sources spaced $\lambda/2$ apart and lying along the x-axis. The desired source is incident on the main beam at 0^o, and the undesired sources are at -60^o and 10^o. Both algorithms nicely place nulls in the desired directions while costing only a small amount of main beam gain.

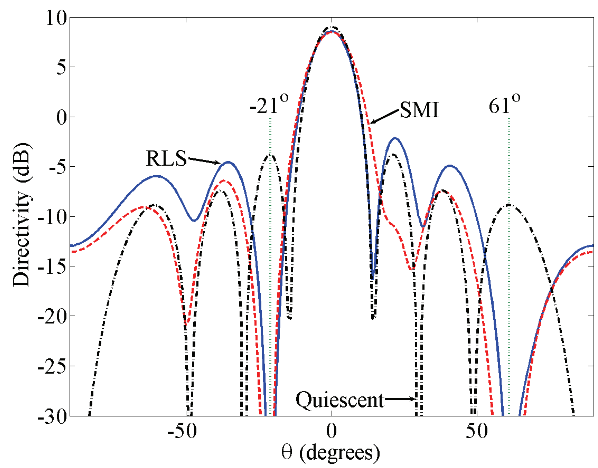

Fig. 11. Adapted patterns using RLS and SMI.

VI. ADAPTIVE NULLING VIA POWER MINIMIZATION

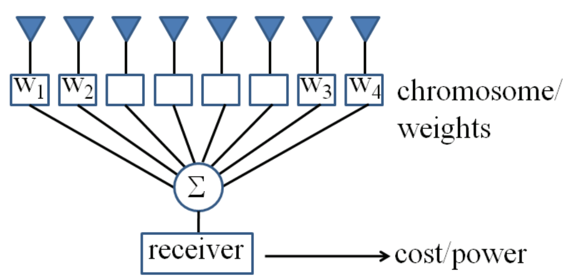

Fig. 12. Diagram of an adaptive array that minimized total output power.

Adaptive nulling described in the previous section has a receiver or AD converter at every element in the array. This approach is a very expensive proposition and requires a method that maintains calibration of all the channels. A much simpler approach makes use of conventional phased array architecture and varies the phase shifters and/or attenuators to minimize the total output power of the array (Fig. **12**). Phase only adaptive nulling has the least amount of hardware requirements of any adaptive nulling approach [20]. A genetic algorithm (GA) [21] has been useful in these types of applications. [22].

If only a few of the elements in the array are adaptive, then nulls can be placed in the sidelobes with little perturbation to the main beam [23]. The weight settings are placed in a vector called a chromosome, and each chromosome has an associated power measurement. A population is a matrix with several chromosomes as rows (Figure 13). The population matrix undergoes natural selection where chromosomes with high output power are discarded. The remaining chromosomes mate and mutate to form new members for the population that replace the members discarded during the natural selection process. The GA iterates until a satisfactory weight setting is found (Fig. **14**). This adaptive nulling approach has been experimentally validated using digital phase shifters and attenuators as the weights [24].

$$\begin{array}{ccc} \begin{array}{cccc} w_1 & w_2 & w_3 & w_4 \end{array} & & \text{dBm} \\ \begin{bmatrix} .12 & .54 & .62 & .98 \\ .44 & .23 & .71 & .38 \\ & \vdots & & \\ .85 & .15 & .22 & .59 \end{bmatrix} & \Rightarrow & \begin{bmatrix} -50 \\ -59 \\ \vdots \\ -63 \end{bmatrix} \\ \text{population} & & \text{cost} \end{array}$$

Figure 13. The weights are placed in a population matrix and the cost is the power received.

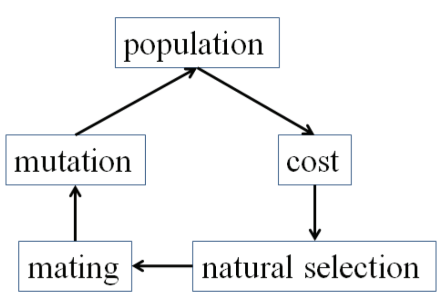

Fig. 14. Flow chart of GA for adaptive nulling.

The 8 element array of $\lambda / 2$ dipoles spaced $\lambda / 2$ apart in Fig. **15** is modeled using the method of moments [25]. A 0 dB desired source is incident at $\phi = 90^o$, and a 15 dB interference signal is incident at $\phi = 68^o$. After 20 generations, the GA having a population of 8 and 15% mutation rate finds the adapted pattern in Fig. **16**. The algorithm placed a 20 dB null in the sidelobe while only losing 1 dB from the main beam.

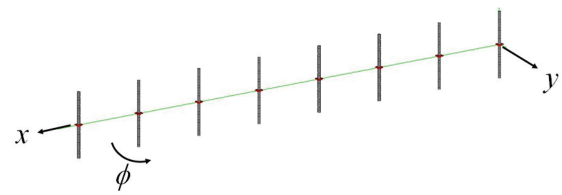

Fig. 15. Adaptive dipole array.

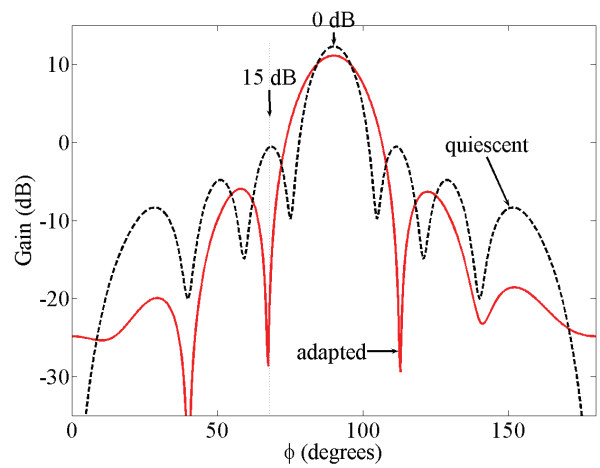

Fig. 16. Adapted and quiescent patterns.

VII. ADAPTIVE ARRAYS WITH RECONFIGURABLE ELEMENTS

Reconfigurable elements come in many forms. One type changes the conductivity of silicon on part of an antenna in order to control its radiation properties [26][27]. An array can be made adaptive using reconfigurable elements (rather than attenuators and phase shifters) and the power minimization approach [28]. Fig. **17** is a model of a patch antenna with a thin strip of silicon between the main patch and a thin metal extension. The conductivity of the silicon is dependent upon the infrared illumination provided from an infrared source at the bottom. Changing the conductivity of that small strip of silicon alters the radiation and impedance of the patch. A graph of the amplitude of the return loss is shown in Fig. **18** for conductivities between 0 and 1000 S/m. The patch is resonant at 2 GHz when the illumination is off.

Increasing conductivity to 1000 S/m causes the patch to resonate at 1.78 GHz. Changing the conductivity from 0 to 1000 S/m, causes the s_{11} at 2 GHz to increase from 0 to 0.9. As a result, the photoconductive silicon acts as an amplitude control for that element. Placing these elements together in an array, as shown in Fig. **19** permits control of the array pattern by changing the illumination of the silicon. The spacing between elements is 75 mm or 0.5λ .

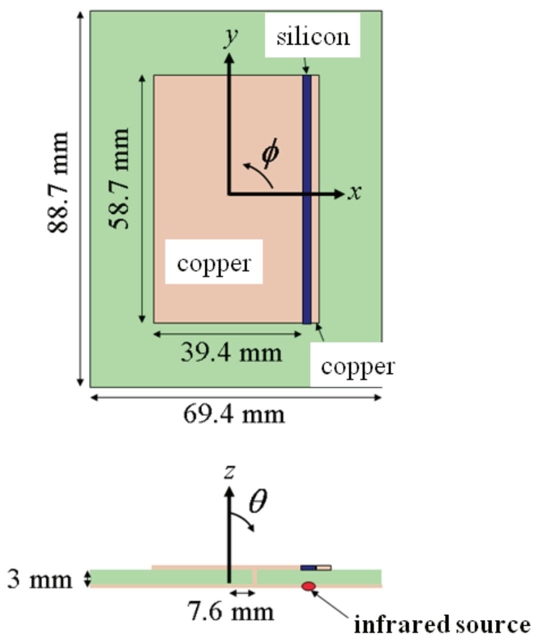

Fig. 17. Reconfigurable patch.

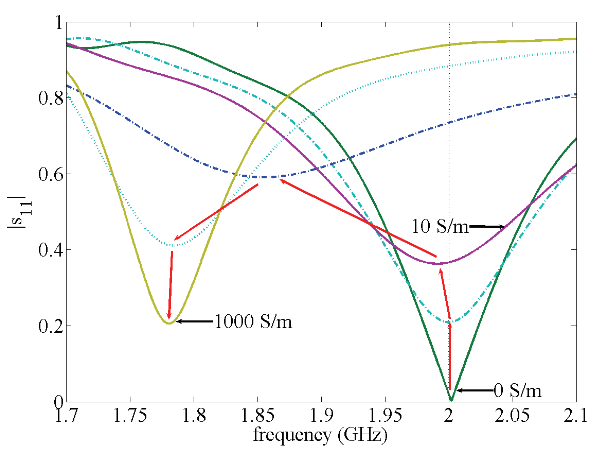

Fig. 18. Reflection coefficient as a function of frequency for several different silicon conductivities.

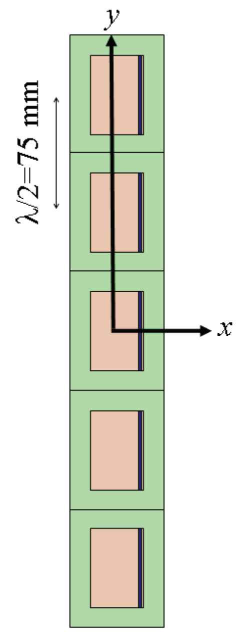

Fig. 19. Linear array of reconfigurable elements.

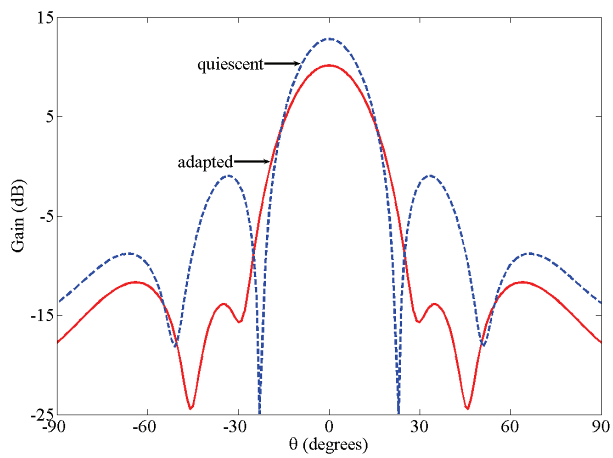

Fig. 20. Quiescent and adapted patterns for reconfigurable array.

If the silicon insets all have a conductivity of zero (illumination off), then the array is uniform with a far field pattern shown in Fig. **20**. The calculations for this example used CST Microwave Studio [29]. This quiescent pattern has a gain of 12.8 dB and a relative peak sidelobe level of 13.8 dB. Illuminating the silicon at each element with a different optical intensity produces a conductivity, hence amplitude, taper across the array. An equal sidelobes array pattern results when the conductivity has values of [16 5 0 5 16] S/m. The corresponding antenna pattern is shown in Fig. **20**. It has a gain of 10.4 dB and a peak relative sidelobe level 23.6 dB below the main beam. Thus, the array can switch from a higher gain, high sidelobe pattern to a lower gain, low sidelobe pattern whenever there is interference entering the sidelobes.

VIII. CONCLUSIONS

Adaptive arrays come in many forms. Many signal processing algorithms exist to automatically place nulls in the sidelobes while keeping the main beam intact. They all rely upon the use of an array with a receiver or AD converter at each element. The costs and calibration requirements limit the use of these arrays. Another approach that minimizes the total output power using a GA limits the main beam reduction by limiting the number of adaptive elements in the array. This type of algorithm works on commonly existing array architectures. Using reconfigurable elements rather than phase shifters and attenuators is a novel approach that needs further testing in an adaptive nulling situation.

ACKNOWLEDGMENT

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