Adaptive Antennas

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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.

Keywords: adaptive antenna, smart antenna, adaptive nulling, reconfigurable antenna, MIMO.

1. 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 – A system has multiple beams and the beam that best receives the desired signal is selected.
2. 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.
3. Direction finding – Automatically detect signals and place nulls in the directions of those signals. An algorithm determines where those nulls are and hence the location of the signals.
4. Retrodirective – Retransmits an incident signal in a desired direction, usually the direction of the incident signal.
5. MIMO – multiple input multiple output – Adaptation occurs at both the receive and transmit arrays of a communications system.
6. Reconfigurable Antenna – An antenna that alters its physical properties (usually through some type of switch) in order to change its resonant frequency or polarization.

This paper starts by describing 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.

2. Historical Development

Antenna arrays are necessary for implementation of almost all adaptive antenna ideas. Direction finding had a giant leap forward when Adcock [1] used four monopole antennas placed on the edges of a square, and Sir Watson-Watt [2] 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 F. Braun [3]. Other antenna array developments centered upon developing low sidelobe amplitude tapers for linear arrays (the $w_n$ in Figure 1). Starting with the impractical binomial taper [4] then progressing to the more practical Dolph-Chebychev [5] and further to the useful Taylor amplitude taper [6]. Along the way, Schelkunoff [7] 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 [8]. Usually, this type of retrodirective array amplifies and phase shifts the receive signal such that it retransmits in the direction of the incident field. At around the same time, the sidelobe canceller was developed in the late 1950's [9]. 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 (Figure 2). 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 [10].
where
\[ \mathbf{w}_{\text{opt}}(\kappa) = \mathbf{R}^{-1}(\kappa) \mathbf{E}[\mathbf{d}(\kappa)\mathbf{s}(\kappa)] \] (1)

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

In the 1960's the least mean square (LMS) algorithm was developed [12] and became the standard. Most adaptive algorithms had 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
\[ \mathbf{w}(\kappa+1) = \mathbf{w}(\kappa) + \mu \mathbf{s}(\kappa)[\mathbf{d}(\kappa) - \mathbf{w}^H(\kappa)\mathbf{s}(\kappa)] \] (2)

where \( \mu \) 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).

### 3. Digital Beamforming vs. Power Minimization

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.

![Digital beamforming array](image1.png)

**Figure 3. Digital beamforming array.**

![Diagram of an adaptive array](image2.png)

**Figure 4. Diagram of an adaptive array using the total output power as the feedback mechanism.**

Adaptive nulling described in the previous section has a receiver at every element in the array. This approach is a very expensive proposition and requires a method that maintains calibration of all the receivers. A much simpler approach makes use of conventional phased array architecture and varies the phase shifters and attenuators and phase shifters to minimize the
total output power of the array (Figure 4). Phase only adaptive nulling has the least amount of hardware requirements of any adaptive nulling approach [13]. A genetic algorithm has been useful in these types of applications. [14].

4. Adaptive Arrays with Reconfigurable Elements

An array can be made adaptive using reconfigurable elements and the power minimization approach [15]. Figure 5 is a model of a patch antenna with a thin strip of silicon near its edge. The conductivity of the silicon is dependent upon the optical illumination provided from a source at the bottom. Changing the conductivity of that small strip of silicon will alter the radiation properties of the patch. Placing these elements together in an array, as shown in Figure 6, allows for control of the array pattern by changing the illumination of the silicon. The spacing between elements is 75 mm or \(0.5\lambda\). A graph of the amplitude of the return loss is shown in Figure 7 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 \(s_1\) at 2 GHz to increase from 0 to 0.9. As a result, the photoconductive silicon acts as an amplitude control for that element.

If the silicon insets all have a conductivity of zero (illumination off), then the array is uniform with a far field pattern shown in Figure 8. This quiescent pattern has a gain of 12.81 dB and a relative peak sidelobe level of 13.84 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 Figure 8. 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.

**Figure 5.** Reconfigurable adaptive element.  **Figure 6.** Adaptive array of reconfigurable elements.
Figure 7. Reflection coefficient of reconfigurable element as a function of frequency and conductivity of strip.

Figure 8. The quiescent pattern (dashed line) occurs when all the optical sources in the array are turned off. The adapted pattern (solid line) occurs when the optical sources are adjusted to yield a conductivity taper of \([16\ 5\ 0\ 5\ 16]\) S/m.
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References