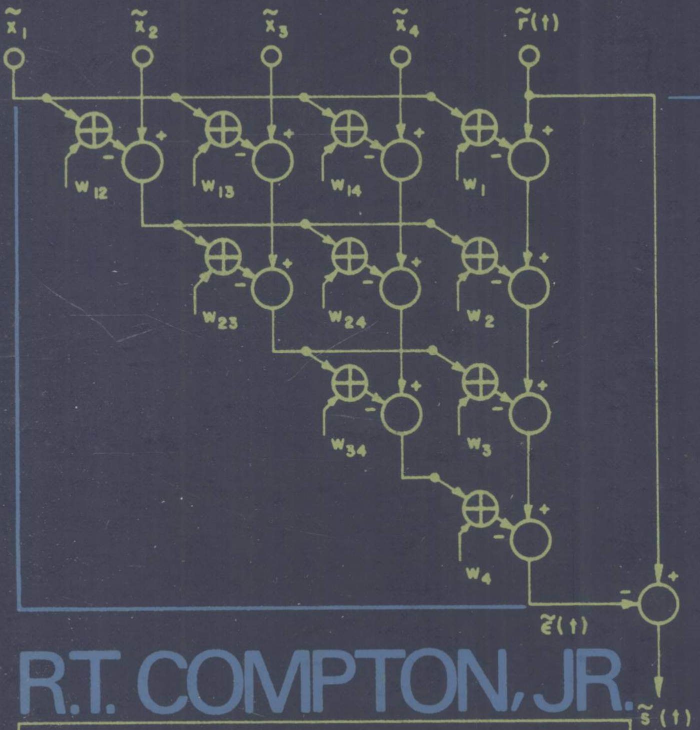
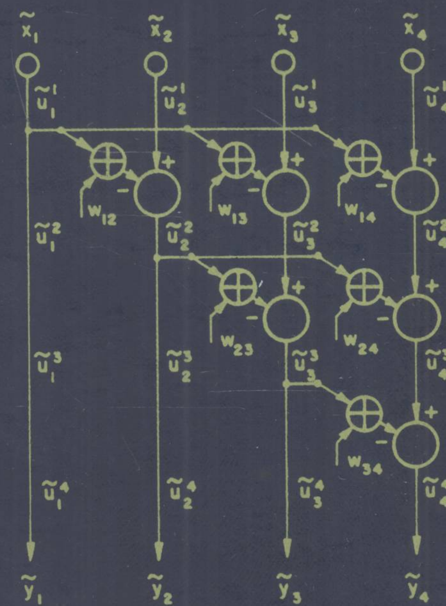
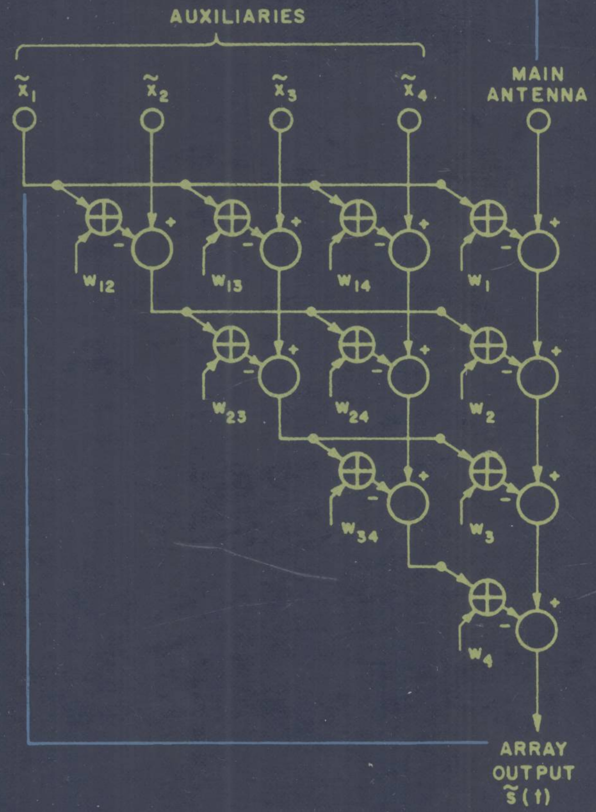


R.T. COMPTON, JR.

ADAPTIVE ANTENNAS

CONCEPTS AND PERFORMANCE





ADAPTIVE ANTENNAS

Concepts and Performance

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ADAPTIVE ANTENNAS

Concepts and Performance

To Lorraine, Diane, Ted, and Chard

Preface

The purpose of *Adaptive Antennas: Concepts and Performance* is to present a unified treatment of adaptive antenna systems and to describe their capabilities and limitations. An additional purpose of the book is to acquaint the reader with the analytical techniques used to predict the performance of these systems in new applications.

The subject of adaptive antennas bridges several disciplines within electrical engineering. The author has found that engineers from different specialties tend to view adaptive antennas from quite different perspectives. Antenna engineers are inclined to ask about antenna patterns, sidelobe levels, null depths, the effects of element patterns, and polarization. Communications engineers tend to regard the adaptive antenna as a time-varying processor. They want to know how signal modulation and bandwidth, signal arrival angles, signal and noise powers, and the number of signals affect output signal-to-noise ratios, bit error probabilities, and the like. Control engineers usually ask about stability and rate of convergence of the adaptive weight control loops.

Our purpose in this book is to present adaptive array concepts in a way that incorporates all of these viewpoints. We freely mix together antenna, communication, and feedback control ideas in the presentation. Our goal is an integrated treatment that addresses all three aspects of the problem.

The book is essentially analytical in nature. We use mathematics as a tool to explain basic concepts and to study adaptive array performance. However, the reader will find that even though the approach is analytical, the emphasis in the book is on practical matters, not on theoretical problems. In fact, much of the material covered represents lessons learned (sometimes painfully!) from hardware development. But we do not go into detailed circuit questions. Instead, we describe the nature of the practical problems that occur and show how to determine the effects of these problems on system performance.

The overall plan of the book is as follows. After some introductory remarks in Chapter 1 about historical background, we begin in earnest in Chapter 2. Chapter 2 presents the adaptive array feedback concepts of Shor, Applebaum, and Widrow et al. and shows how to analyze these systems. The major emphasis in the chapter is on the least-mean-square (LMS) and Applebaum arrays, in both the continuous and discrete forms. Simple examples are given that show how an adaptive array accomplishes its major purpose: tracking a desired signal and nulling interference. Chapter 2 also serves to introduce analytic signal notation and the covariance matrix, shows how the array speed of response and stability are controlled by the covariance matrix eigenvalues, and proves that the maximum signal-to-interference-plus-noise ratio (SINR) criterion of Applebaum and the minimum mean square error criterion of Widrow are equivalent. The purpose of Chapter 2 is to introduce basic concepts and show how adaptive antennas work under idealized conditions.

Next, Chapters 3 and 4 discuss the practical effects that actually control the performance of adaptive antennas. Chapter 3 considers three factors important in all adaptive arrays, regardless of the weight control technique used: the number of degrees of freedom in the array, the signal bandwidths, and the element patterns. The concept of degrees of freedom is discussed from several viewpoints, and we show what happens when the number of signals exceeds the number of degrees of freedom. Bandwidth effects are analyzed in a general way to show how arbitrary desired signal and interference power spectral densities may be handled in an adaptive array analysis. To illustrate typical results, we compute the array performance for signals with flat, bandlimited spectral densities. Element pattern effects are also handled in a general way. Since element patterns cannot be defined without taking signal polarization into account, we also discuss polarization in the same section. We use the Poincaré sphere to characterize polarization. We show how to determine the performance of an adaptive array with arbitrary elements when it receives signals with arbitrary polarizations. Simple arrays of cross-polarized dipoles are used to illustrate typical results.

Chapter 4 continues the discussion of practical effects but concentrates on aspects particularly associated with the LMS array. Feedback loop bandwidth, feedback loop time delays, multiplier offset voltages, and weight saturation are described. The IF feedback loop is introduced as a method of avoiding multiplier offset voltages. Weight jitter is described and a method is presented for analyzing it. Finally, covariance matrix eigenvalue behavior is described. We show how eigenvalues depend on signal arrival angles, signal powers, signal bandwidths, number of signals, number of elements, element spacing, and element patterns. Chapter 4 summarizes many practical lessons learned in building LMS loops for adaptive arrays.

In Chapter 5 we turn to more advanced methods of weight control in adaptive arrays. Because of the pervasive problem of eigenvalue (or time constant) variation, researchers have tried to develop methods of weight control less sensitive to eigenvalues than the LMS array. Chapter 5 presents four of these methods: the modified LMS loop, the Gram-Schmidt processor, the recursive least-squares algorithm, and the sample matrix inverse method.

Next, Chapter 6 presents a variety of topics related to the steered beam, or Applebaum, array. We first describe the sidelobe canceler and discuss its relationship to the general Applebaum array. We show how the Applebaum array may be arranged into other equivalent forms by including a preweighting network in front of the adaptive processor. We examine the sensitivity of the Applebaum array to steering vector errors, a subject of some importance when an Applebaum array is used in a communication system. We present the Frost array, which is an adaptive array that incorporates constraints in its pattern or frequency response. Finally, we discuss the power inversion array, a special case of the Applebaum array.

We conclude the book in Chapter 7 by describing methods of using an LMS array in communication systems. The LMS array is attractive for communication applications because it can automatically track the arrival angle of an incoming desired signal. However, in order to do so, the array feedback must be supplied with a reference signal correlated with the desired signal and uncorrelated with interference. Since in general it is not obvious how such a reference signal may be obtained in a practical communication system, the purpose of Chapter 7 is to give a few examples of communication systems where this can be done. Unfortunately, the story is far from complete in this area, and research is continuing. Hopefully, the material in Chapter 7 will suggest additional ideas to the reader.

The book is intended to be used both as a graduate textbook and as a reference book for workers in the field. The manuscript was used twice as a text for a graduate course in the Electrical Engineering Department at Ohio State University. Students taking this course needed only an undergraduate background in electrical engineering. The book assumes the reader knows what a Hermitian matrix is, what the eigenvectors and eigenvalues of a matrix are, and what a coordinate transformation with matrices looks like. Also, a few elementary concepts in random variables and random processes are used. A student who has taken a course in matrices and one in random processes is ideally prepared. However, since only the simplest ideas from these fields are actually used, an instructor can easily fill in the desired background if necessary. The book uses feedback control terminology and discusses antenna patterns, but the presentation is self-explanatory, and no additional background in either controls or antenna theory is required. As noted previously, the Poincaré sphere is used to describe polarization. Since this concept will not be familiar to most electrical engineering students (unless they have specialized in electromagnetics), it is presented in such a way that no real background is required. The book includes homework problems to test the student's understanding of the subject matter and to give practice in analyzing array performance in various situations. A number of the problems discuss concepts or performance questions not covered in the text. Also, several of the problems require a programmable calculator or small computer to obtain numerical results.

For an engineer working in the field, the book can serve as a reference that unifies the antenna, communications, and feedback control aspects of the subject. An antenna engineer, for example, will find the book useful for learning how a reference signal is obtained for an adaptive array in a communication system, or for seeing how to take signal bandwidth into account in a performance study. A communications engineer will learn how element patterns and polarizations affect signal-to-noise ratios and array speed of response, as well as how to choose loop gains so the array does not modulate the signal. Our goal in this book has been to address the whole problem.

Writing a book is a humbling experience. One begins with grand ideas, but because of the immensity of the task, one is forced to compromise between the conflicting goals of perfection and getting the thing done. Moreover, because writing a book takes a few years, one has the unsettling experience of seeing new research papers continually appear while the book is being written. One can only watch nervously and hope that some novel paper will not throw the book out of date before it is even finished. Also, because at some point one must stop revising and simply finish, some things inevitably are not included. To my fellow workers in the field who find their favorite paper missing from the book, I can only apologize.

I am indebted to a large number of people for their help in this project. First and foremost I must thank Mr. Jim Willis and the Naval Air Systems Command, whose support has been absolutely essential. Many years of research support provided by Naval Air Systems Command made this project possible. In addition, I am indebted to Professor H. C. Ko, Chairman of the Electrical Engineering Department at Ohio State University, for allowing me time for this project and for making secretarial help available. My friends and colleagues in the ElectroScience Laboratory at Ohio State have contributed immeasurably by teaching me many things about adaptive arrays. In this regard, I am particularly indebted to Professor A. A. Ksienski, Dr. R. J. Huff, Dr. W. G. Swarner, and Dr. I. J. Gupta. I am greatly indebted to Ms. Emily Baird and Ms. Jacqueline Buckner for their diligent and professional job of typing the book from my cluttered manuscripts. Also, I am very grateful to the students in two classes who persevered through the manuscript, offered helpful suggestions for improvements, pointed out many typos and clumsy spots, and the like. Finally, I want to thank my wonderful wife and family for their encouragement and their patience during many long absences.

R. T. Compton, Jr.
Columbus, Ohio

ADAPTIVE ANTENNAS

Concepts and Performance

Contents

1

Introduction

An adaptive antenna is an antenna that *controls its own pattern*, by means of feedback control, while the antenna operates. Some adaptive antennas also control their own frequency response. All adaptive antennas to date have been arrays, rather than continuous aperture antennas, because the pattern of an array is easily controlled by adjusting the amplitude and phase of the signal from each element before combining the signals. Since adaptive antennas are in fact arrays, we shall use the terms *adaptive antennas* and *adaptive arrays* interchangeably in this book. Also, the adaptive antennas we discuss are receiving antennas. We do not consider transmitting antennas.

Adaptive antennas are useful in radar and communication systems that are subject to interference and jamming. These antennas change their patterns automatically in response to the signal environment. They do so in a way that optimizes the signal-to-interference-plus-noise ratio at the array output. Thus they are especially useful for protecting radar and communication systems from interference when the arrival direction of the interference is not known in advance. In communication systems, they are also useful when the desired signal arrival angle is unknown, since an adaptive array pattern can automatically track the desired signal direction. Adaptive arrays can operate with somewhat arbitrary element patterns, polarizations, and spacings. They do not require uniform element spacings or identical element patterns in the array. This feature is an advantage when an antenna system must be designed to operate on an irregularly shaped surface, such as that of an aircraft.

Adaptive antenna systems can be said to date from the 1950s. In 1956, Altman and Sichak [1] proposed the use of phase-lock loops for combining the

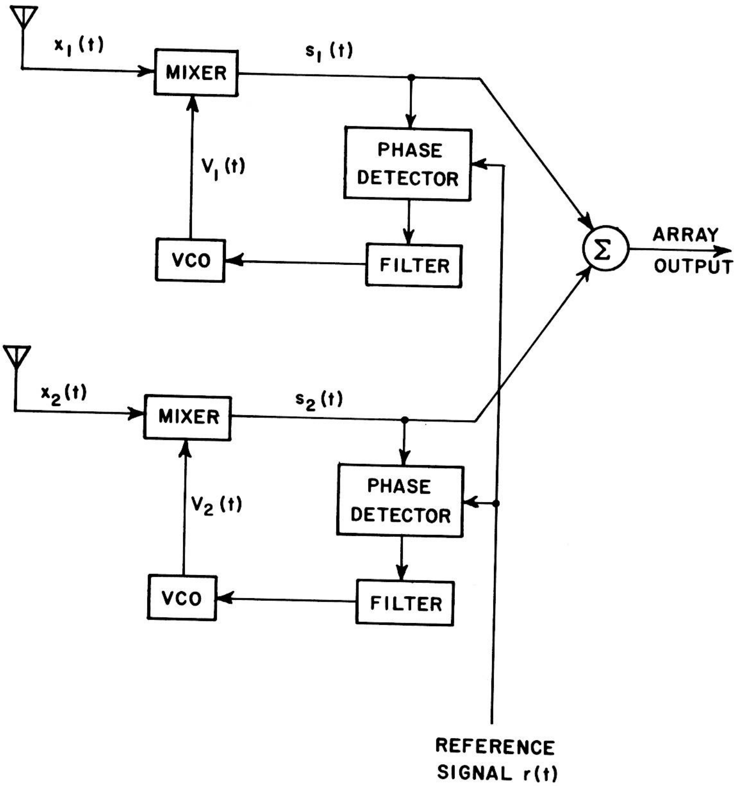

Figure 1.1 The phase-lock loop array.

signals from different receiving antennas in a diversity system. In the 1960s phase-lock loop arrays were extensively studied. Some typical phase-lock loop systems are described in a special issue on active and adaptive antennas of the *IEEE Transactions on Antennas and Propagation* in 1964 [2], edited by R. C. Hansen. See, for example, the papers by Ghose [3], Eberle [4], and Svoboda [5].

A phase-lock loop array operates by aligning the phase of the signal from each element with that of a reference signal, before summing the signals to produce the array output. A block diagram of a phase-lock loop array is shown in Fig. 1.1. The signal from each element is passed through a phase-lock loop‡ that automatically aligns its phase with that of a reference signal. In Fig. 1.1, element signal $x_1(t)$, for example, is mixed with signal $v_1(t)$ from the voltage-controlled oscillator (VCO). The mixer output $s_1(t)$ appears at an IF frequency. The phase of $s_1(t)$ is determined by both $x_1(t)$ and $v_1(t)$. The phase difference between $s_1(t)$ and a reference signal $r(t)$ is derived in a phase comparator, and

‡Phase-lock loops are extensively discussed in Viterbi [6].

this phase difference is used to adjust the VCO until $s_1(t)$ is in phase with $r(t)$. The same reference signal $r(t)$ is used for all elements, so the signals $s_1(t)$, $s_2(t), \ldots$ from different elements are in phase and can be added to yield maximum array output signal power.

A phase-lock loop array is adaptive because the antenna pattern is controlled by the incoming signal direction. The array automatically forms a beam that tracks the signal. Moreover, amplitude control can be incorporated in a phase-lock loop array. Svoboda [5] discussed a method for making the gain behind each element proportional to the signal voltage and inversely proportional to the noise power. If this technique is used, the array becomes a maximal ratio combiner [7]. That is, it yields maximum possible signal-to-noise ratio at the array output.

However, the phase-lock loop array has a serious drawback: It is vulnerable to interference. Because the phase-lock loops can track only one signal at a time, the array is easily confused if more than one signal is received. If an interference signal arrives that is stronger than the desired signal, it can easily capture the beam of the antenna. Figure 1.2 (from Svoboda [5]) illustrates this problem in a typical situation with two signals. In this figure the vertical axis is the power ratio of the two signals. The horizontal axis is the frequency difference between the two signals. In the shaded region, the array will not track the desired signal properly. Suitable operation is obtained only if the interference falls in the unshaded region—that is, only if its power is too weak or if its frequency is too far off to capture the phase-lock loops.

Because phase-lock loop arrays are vulnerable to interference and jamming, interest in them has waned in favor of newer types of adaptive arrays,

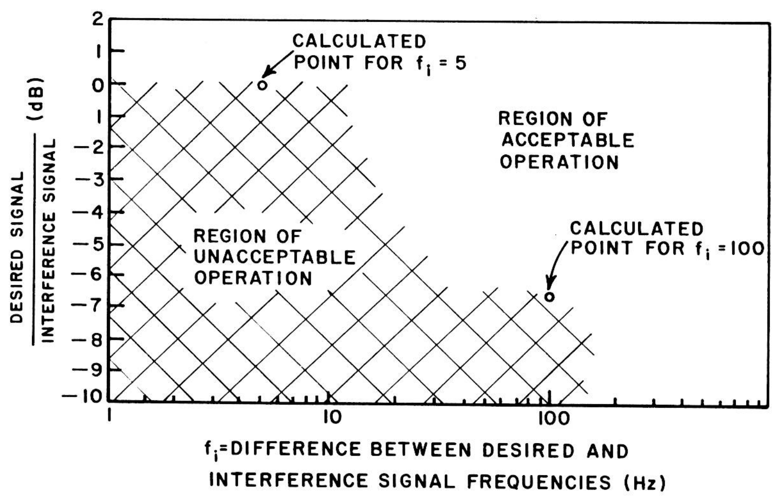

Figure 1.2 Regions of acceptable and unacceptable operation (reprinted from Svoboda [5] with permission, © 1964 IEEE).

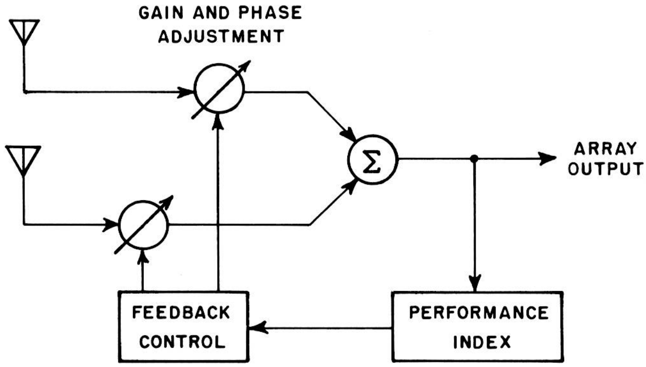

Figure 1.3 A general adaptive array.

such as the LMS and Applebaum arrays to be discussed in Chapter 2. These arrays not only can track a desired signal and maximize array output signal-to-noise ratio, they can null interference as well. The approach used in these arrays is more general than in the phase-lock loop array. The signal from each element is adjusted in both gain and phase, as shown in Fig. 1.3, and the adjustment of the gains and phases is treated as an adaptive optimization problem. That is, a performance index is defined, such as array output signal-to-interference-plus-noise ratio, and the gains and phases are controlled to maximize this performance index.

The performance index that should ideally be used depends on the application. If the array is used in a digital communication system, the ideal performance index is bit error probability. We should choose the array gains and phases to minimize this probability. If the array is used in a radar, we should maximize signal detection probability for a given false alarm probability. However, it turns out that these ideal performance indices are difficult to evaluate directly at the array output. In lieu of these, two other optimization criteria are actually used: (1) minimum mean-square error between the actual array output and the ideal array output and (2) maximum signal-to-interference-plus-noise ratio (SINR) at the array output. The first of these leads to the LMS array and the second to the Applebaum and Shor arrays. These performance indices are more fruitful than the ideal ones because they lead to useful forms of feedback for controlling the array pattern. Moreover, bit error probability always decreases with SINR and radar detection probability always increases with SINR, so these more practical criteria are essentially just as good.

It should be pointed out that with adaptive arrays we do not usually try to control certain conventional antenna characteristics, such as antenna gain, beamwidth, or sidelobe levels. These conventional characteristics are not useful as performance indices in the adaptive array problem. Consider the question of sidelobes, for example. Low sidelobes are desirable in a conventional antenna to minimize the effect of unwanted radiation coming from outside the main beam. However, an adaptive array eliminates unwanted radiation in an entirely different way. It places a pattern null on the interference. The pattern of an adaptive array will frequently have high sidelobes, but only in directions from which no interference comes. For that reason, these high sidelobes are of little consequence. In general, conventional antenna criteria are of less interest with adaptive arrays than more fundamental objectives, such as maximizing SINR.

With this background, we are ready to begin. In Chapter 2, we shall introduce the adaptive array concepts of Shor, Applebaum, and Widrow et al. and show how these antennas work under idealized conditions. In Chapters 3 and 4, we shall examine factors that affect their actual performance under nonideal conditions.

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