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Introduction

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1.1 Aims and Scope

A fundamental problem confronting the designer of antenna arrays is that the excitation of an individual element is not directly proportional to the applied source. This is a result of the array elements interacting with each other through the electromagnetic field, which induces currents on all antennas present in addition to those on the driven element. This interaction is called mutual coupling. Since the radiation characteristics of the elements are different in the array environment, all properties of the array, such as the gain, beam width, and input reflection coefficients, are affected by mutual coupling (Bird 2016). Another effect is that, in arrays of waveguides and horns, modes other than the primary ones may be excited, which can cause array blindness, reflection resonances, and depolarization. Mutual coupling is polarization dependent, and its effect is generally strongest when the inter-element spacing is small. The effect of mutual coupling is not all deleterious, however. Some arrays use, for example, parasitically excited elements to enhance performance. In the last few years, mutual coupling has also been used to improve the performance of arrays by placing the elements closer together so as to create an effective sheet of current. Antennas in arrays or those connected unintentionally have occurred in a wide variety of applications over the years as illustrated in Figure 1.1. The examples shown in Figures 1.1a and 1.1b are early warning radar antennas, the SCR-270 from the 1940s (Stitzer et al. 2007) and the PAVEPAWS array dating from the 1970s (Brookner et al. 2010), respectively. PAVEPAWS is a network of early warning radars. Each face of the array shown in the figure is about 27m in diameter and consists of over 1790 bent, crossed dipoles. The light weight array of horns shown in Figure 1.1c was a standard method of generating shaped beams with a reflector in the 1990s. The feed array in the figure produced a shaped beam for continental USA and Hawaii (Bird and Sroka 1992). Wireless communications in the 2000s have been dominated by the development of multiple input multiple output (MIMO) systems. Figure 1.1d shows a set of dual-band MIMO base station antennas (Guo and Jones 2018) with the cover removed. Platforms and towers with many co-sited antennas such as in Figures 1.1e and 1.1f show clustering which creates potential for coupling in a base station and on a warship, respectively.

The topic of this book is integral to many antenna configurations and is fundamental to understanding their operation. Yet, in the past, before modern computer software, its effect was often neglected when designs were prepared. This is because mutual coupling affects were taken to be of a secondary nature. It is assumed that a design without considering its influence could still provide

Mutual Coupling Between Antennas, First Edition. Edited by Trevor S. Bird.
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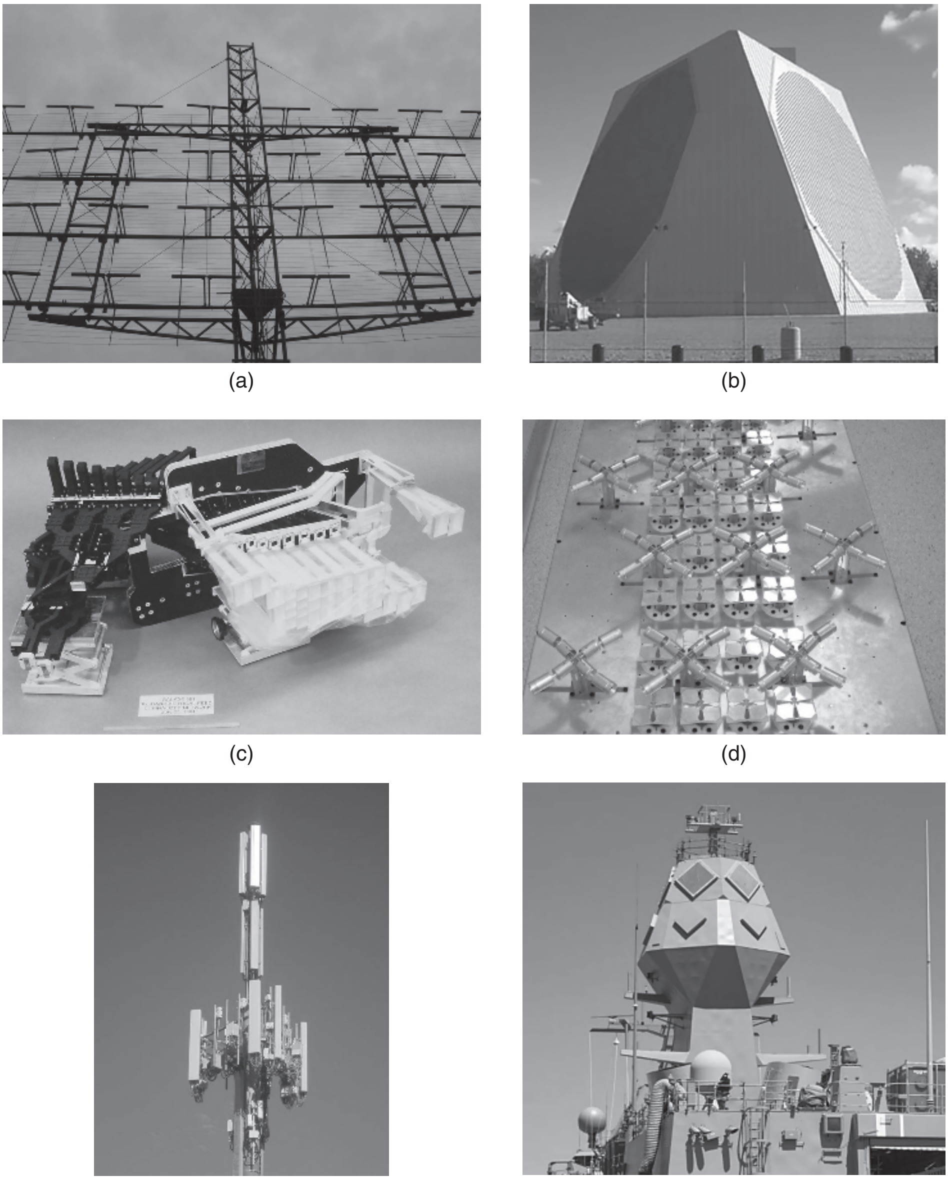

(a) (b) (c) (d) (e) (f)

Figure 1.1 Arrays of antennas over the past 80 years in which mutual coupling has a role. (a) One of the first operational early warning radar sets, the SCR-270 deployed in the 1940s, had 32 dipoles in front of a reflecting mesh. Source: brewbooks, https://commons.wikimedia.org/wiki/Category:SCR-270_radar#/media/File:SCR-270_Radar_Antenna2.jpg, CC BY-SA 2.0; (b) the AN/FPS-123 PAVEPAWS phased array radar at Clear Air Base, Alaska (USA) upgraded from earlier models dating from the 1960s (U.S. Army Corps of Engineers). Source: U.S. Army Corps of Engineers Alaska District; (c) a feed array for shaped beam reflector on Galaxy IV satellite in the 1970s. Source: Courtesy of Hughes Space and Communications Group; (d) dual-band multiple input multiple output arrays showing the inter leaved LTE (long-term evolution standard for mobile communications) low- and high − band dipoles. Source: Courtesy of Argus BSA; (e) unintended interaction of antennas on a repeater tower in 2010s. Source: Trevor S. Bird; and (f) co-sited antennas including arrays on frigate HMAS Arunta in the 2000s. Source: Courtesy of Royal Australian Navy.

an approximate expectation of performance. Further, its inclusion in a physical model requires detailed consideration of Maxwell's equations, which, to this day, many engineers try to avoid. Some antennas have a well-established design methodology that allows mutual coupling to be circumnavigated using lumped circuit elements or high-frequency approximations.

The intention of this book is to cover the main techniques that depend clearly on an understanding of the physics through Maxwell's equations. While detailed design is possible through the several accurate computer packages that are readily available, a greater understanding of what may be possible and is achieved through connection with the physics often with simple models. Several approaches will be described, including lumped networks, which should enable both better design and understanding of the physics involved in a more comprehensive manner than hitherto available. The resulting formulations, and several are possible, are applied to a variety of practical antenna configurations and geometries. This includes antennas such as tightly coupled arrays that inherently make use of mutual coupling to increase performance as well as antennas that operate nearby each other, such as those mounted on a mast or ship, where they can interact with a resulting modification in performance. The influence of mutual coupling on stand-alone antennas such as in radar direction finding is considered. In these and other applications, mutual coupling can be undesirable and, as a result, techniques for reducing its effects are important. A range of techniques for doing this is covered here as well. By contrast, some modern-day communications are made possible by means of MIMO systems which require several antennas in close proximity, and this interaction is considered in detail, as well as large, dense arrays of elements that also make inherent use of mutual coupling. The range of array applications is such that the variety of antenna geometries considered here range from arrays of wire antennas to arrays that conform to surfaces such as a cylinder or a sphere. At all times, the intention is to use the basic physics of the problem and Maxwell's equations in its many manifestations. The material in the chapters is well supported by references and appendices.

1.2 Historical Perspective

Mutual coupling was recognized as important by the early pioneers in electromagnetics and antenna theory. Brillouin (1922) was probably one of the earliest to detail a method of analysis, and like many early workers, he was concerned mainly with calculating radiation resistance rather than the complex impedance at the input of array elements. A systematized approach, called the *electromotive force (emf) method*, was applied by Pistolkors (1929) to find the radiation resistance of various dipole array configurations. Another approach adopted at that time was the Poynting vector method, the present-day text book method of calculating radiation resistance from the integrated normal energy flow through a surface surrounding the antenna. This second approach was used, for example, by Bontsch-Bruewitsch (1926) and Knudsen (1952). Both approaches are equivalent and can be converted into the other by means of Gauss's law, as shown by Bechmann (1931). The emf method gained wider acceptance after the work of Carter (1932), who used reciprocity and the emf method to determine expressions for self and mutual impedances for a variety of two-dipole arrangements. This expression for the self-impedance was also derived by Richmond (1961) from the Lorentz reciprocity theorem. Formulae for the mutual impedance of two dipoles in various geometrical arrangements have been derived from assumed currents, and some of these are given by Brown (1937), Barzilai (1948), and Hansen (1966). Storer (1952) developed a variational method to calculate mutual impedances. More sophisticated coupling configurations were subsequently investigated, including the coupling between unequal-size dipoles by Levis and

Tai (1956). Measurement of mutual impedance in dipole arrays was commenced in the 1930s, and the techniques used were described by Carter (1932) and Brown (1937) who detailed a technique for measuring the mutual impedance of elements in the broadcast frequency band.

Carter's paper profoundly influenced much of the subsequent literature on antenna coupling because for the first time the coupling problem was expressed as an equivalent circuit. All the above-mentioned papers were concerned with dipole elements. Slot coupling such as in a waveguide was investigated by Stevenson (1948). However, prior to that, Booker (1946) had identified the complementarity of dipole and slot antennas through Babinet's principle of duality. This paper led to subsequent research on slot antennas, which had been tried during the early 1940s, in the same way Carter did with dipoles. Complementarity was applied by Compton (1950) to slot antennas and the principle was used by Surtees (1950) to obtain the coupling between a slot and a dipole. Expressions for mutual coupling were also derived from duality by Begovich (1950). Other results followed including the derivation by Yee (1961) of the mutual admittance between two magnetic line sources.

The analysis of periodic structures by Floquet's method (e.g. see Collin 1960; Amitay et al. 1972) had been used for decades in solid-state physics (e.g. Merzbacher 1961) before its adoption for antenna arrays in the 1960s even though the significance of periodicity was recognized earlier by Wheeler (1948). The Floquet method found favor at that time for a range of array structures and provided an early means of understanding coupling effects and for analyzing the performance of large arrays. One of the first to apply this approach to a large array was Edelberg and Oliner (1960). An impetus for this was the discovery of unexpected radiation pattern nulls at small scan angles, which stimulated greater investigation of mutual coupling effects. Some of this work is reported by Amitay et al. (1972) and Stark (1974). These pattern nulls were later found to be due to the presence of high-order modes excited in the wave guide apertures by mutual coupling and also the excitation of surface waves on the array aperture. The infinite array solution was also applied to medium-sized arrays where edge and corner effects are important and, therefore, this approximation had varying degrees of success. This led in the 1960s and 1970s to the development of methods to analyze mutual coupling in finite arrays. The methods developed were improved through the 1980s and 1990s as computers and software became more capable. At the same time, the development of numerical methods and computer codes allowed the analysis of more complicated antennas including antennas consisting of several different types of complex elements. The computer codes available today allow mutual coupling to be included as a matter of course. Even so, the physical aspects of mutual coupling needs to be understood to minimize the disadvantages and make full use of the advantages. Indeed, in some applications such as in onboard satellite communications, mutual coupling can provide benefits when even a small gain increase of 0.5–0.6 dB, for example, can result in substantially reduced costs and weight carried into space as well as reduced power consumption.

1.3 Overview of Text

Most antennas are subject to various forms of mutual coupling whether due to internal or external effects. Of the internal kind, antenna arrays are the most important antenna type influenced by it. They are common place in modern systems used for communications, radar, environmental monitoring, and radio astronomy. An antenna array is any group of antennas that are excited together for the purpose of producing a prescribed radiation pattern. Examples of some arrays are pictured in Figure 1.1. Arrays are used because the antenna designer is able, within limits, to tailor the radiation pattern as needs require. The limits are determined by fundamental physics such as the radiation pattern of the elements, the number of elements, element spacing, the physical size of the array, and ohmic losses as well as mutual coupling between the elements.

The interaction of antennas through the electromagnetic field known as mutual coupling is explored through Maxwell's equations, analysis, models, and applications. By highlighting some of its effects, it is intended that the physics of this coupling will become more widely known. It is hoped that with better understanding and modeling, it will be standard practice to include mutual coupling in all design and synthesis of the arrays. There are 14 chapters in this book of which the first 7 are authored by the editor. In Chapter 2, a simplified field model of mutual coupling is introduced. The initial approach is through an incremental form of Maxwell's equations and an inverse square law that applies to a small radiating current element. This enables a simple and direct approach to understanding the presence of mutual coupling in a radiating system. The impact of mutual coupling on the far-field radiation is analyzed and demonstrated through magnetic currents and the dual problem of electric currents. The results obtained in Chapter 2 are applied in later chapters to specific current distributions.

Many of the most important techniques that are used in the analysis and computation of mutual coupling are introduced in Chapter 3. Most of these techniques are used in later chapters. Antenna radiation relies on the reciprocity theorem which links currents and fields. Arising from this theorem is the concept of reaction, which is reviewed. Following the definition of circuit quantities, the chapter specifies these quantities for finite and infinite arrays. The former follows as an extension from two to many elements, while in infinite arrays, periodicity naturally creates a cellular approach within which all details of an element are contained for analysis. Most coupling problems are expressed in the form of integral and differential equations, and a common way to solve these is through the method of weighted residuals, which is described. Within the class of weighted residuals is included many of the common methods such as Galerkin's method and the method of moments. Special techniques for coupling problems are briefly described through the method of characteristic modes and minimum scattering. Finally, some particular numerical methods involved in mutual coupling problems are discussed.

In the following chapter, Chapter 4, dipole arrays are studied through a combination of methods. The background and basic tools for studying wire antennas is described in this chapter to give physical insight into the designs using more sophisticated elements. This description has been supported by practical examples and some measurements. Integral solution techniques have been supported by asymptotic approximations, which are shown to provide useful results when elements are at least a wavelength apart.

An analysis of mutual coupling in finite arrays of different-sized wave guides and horns is described in Chapter 5 using an approach based on a Greens function approach. A range of practical problems are analyzed by this method and expressions obtained for the mutual admittance of all possible combinations of mode coupling. A formula is derived for reducing the order of integration in these expressions, allowing the quadruple integral for mutual admittance to be expressed as the sum of four double integrals in the most general case. The present approach is particularly useful for analysis of large arrays where the formulation can be expressed in efficient code enabling large arrays to be analyzed. The elements range from rectangular, circular, and elliptical as well as to dielectric-and metamaterial-loaded apertures.

Chapter 6 describes the coupling present in microstrip patch antennas arrays. Three approaches are described for coupling between different patches. These were the E-and H-field methods and a full-wave approach. Examples will be given of each approach and compared with measured results.

In Chapter 7, a general formulation for the analysis of mutual coupling on concave surfaces is described. This formulation is based on a blend of canonical asymptotic solutions for the electric and magnetic currents on the surface on a cylinder and a sphere. These canonical solutions are studied separately, and results are obtained for mutual coupling between apertures on surfaces with varying sizes of radius of curvature. Some examples of the use of the general formulation are given for a variety of arrays on a circular cylinder, a sphere, and an ellipsoid.

In Chapter 8, coauthored by Derek McNamara and Eloy de Lera Acedo, describe techniques for analyzing mutual coupling effects of the external kind such as in co-sited antennas and antennas on platforms. The extent of the effects depends on the type of antenna, its isolated directivity, its location on the platform, and the geometry of the platform. Examples are given of antennas mounted on platforms and the assessment of the level of mutual coupling from direct electromagnetic field computations.

A frame work for understanding and computing the effects of mutual coupling in MIMO systems is given in Chapter 9 by contributor Karl Warnick. Mutual coupling impacts MIMO systems in a number of areas, and these are discussed. In the receiving array, strong coupling leads to poor active impedance matching and decreased signal-to-noise ratio (SNR) at the receiver output. Most importantly, a highly coupled array generally has high correlation between the received signals at the array elements and fails to achieve the desired antenna diversity that is at the heart of the increased capacity that MIMO systems are expected to realize. The analytical framework developed in the chapter can be used to model fully all coupling effects from end to end in a MIMO system.

The performance of direction-of-arrival (DOA) estimation in the presence of mutual coupling using linear arrays with different inter element separation and general array apertures is studied in Chapter 10, which is coauthored by Antony Lui and Trevor Bird. Initially, DOA estimation performance is evaluated under an ideal situation using point detectors such that the impact of inter-element separation and array aperture to the accuracies of the estimation is apparent. Mutual coupling is neglected in most antenna synthesis procedures, and this has resulted in suboptimum designs. Maximum gain solutions in the presence of mutual coupling are described for single and multiple beams, although without optimization, there is no guarantee that the solution is better than the ideal situation in the absence of coupling. As an example of optimization, a pattern synthesis is described which includes mutual coupling. In the receive mode, the effect of mutual coupling between elements forms part of the received signals that degrades the estimation performance. The impact of number of array elements within a fixed aperture with monopole antenna elements is studied. It is shown that effective mutual coupling compensation can be achieved using a receiving mutual impedance method.

The following chapter, also co-authored by Antony Lui and Trevor Bird, deals with minimizing mutual coupling in arrays. The desire to achieve the array performance at or near the uncoupled case means that techniques for minimizing mutual coupling will always be in demand. The techniques described include conventional methods as well as some new approaches, for example, a method that uses additional parasitic elements in the array with reactive loading to modify the system scattering matrix and improve performance.

Arrays are increasingly being used for receiving applications, and therefore, the noise performance in the presence of mutual coupling is of importance. In Chapter12, Christophe Craeye et al. show that in densely packed arrays, the traditional noise budget based on noise figure of the amplifier is incomplete. Direction-dependent noise at the output of beamformer, such as thermal noise from the environment, needs to be included. A link is established with the co-polar directivity of the array. In all cases, the accurate computation of the noise budget increasingly relies on the ability to efficiently evaluate standard array quantities such as the array impedance matrix and embedded element patterns.

In Chapter 13, methods for analyzing mutual coupling in large arrays are detailed by Christophe Craeye and HaBui Van. Numerical methods are an essential tool for large array design when mutual coupling is included. Different categories of methods are available, based on Maxwell's equations in differential or integral forms. The latter present an advantage for the study of large arrays made of identical elements, although clever combinations between integral and differential techniques also facilitate the analysis of arrays made of complex elements. Some techniques such as macro basis functions are attractive for the analysis of large arrays. Several techniques are described, and examples are provided.

An important aspect of the study of mutual coupling in arrays is the measurement of its effects. In Chapter 14, techniques used for the measurement of mutual coupling are outlined by Alpha Bah and Trevor Bird. Two basic approaches are adopted, depending on whether the arrays have static beams or are phased so that the beams scan. Accurate methods using vector network analyzers are described for both approaches as well as some basic precautions to achieve greater accuracy. Some radiation methods for determination of coupling effects are described as are measurements of radiation characteristics with an emphasis on mutual coupling effects. The chapters are supported by eight appendices, located at the end of the book.

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