

MULTIFUNCTIONAL ANTENNAS AND ARRAYS FOR WIRELESS COMMUNICATION SYSTEMS



Edited by
Satish K. Sharma
Jia-Chi S. Chieh


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**Multifunctional Antennas
and Arrays for Wireless
Communication Systems**

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Edited by

Satish K. Sharma and Jia-Chi S. Chieh
San Diego State University
San Diego, CA, USA

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To our parents, teachers, and family members

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List of Contributors

Behrouz Babakhani

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA

Sonika P. Biswal

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA

Jia-Chi S. Chieh

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA

Kumud R. Jha

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA
Department of Electronics and
Communication Engineering, Shri
Mata Vaishno Devi University, SMVD
University, Katra, India

Saeed I. Latif

Department of Electrical and
Computer Engineering, University of
South Alabama, Mobile, AL, USA

Sima Noghianian

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA

Satish K. Sharma

Antenna and Microwave Lab (AML),
Department of Electrical and
Computer Engineering, San Diego
State University, San Diego, CA, USA

Preface

Multifunctional antennas and arrays are the new trend in the field of antennas for diversified applications such as wireless and satellite communications as well as for radar applications. Reconfigurable antennas starting from frequency reconfiguration, pattern reconfiguration to polarization reconfiguration and their combinations make these antennas not only multifunctional but also reduce space requirements on the host communication devices. In the last two decades there has been great efforts to design and realize these reconfigurable antennas and we anticipate even more efforts to come in the near future. A wide range of sub-topics as they apply to multifunction antennas and arrays include the design and development of the reconfigurable multiple-input-multiple-output (MIMO) antennas, liquid metal antennas, piezoelectric antennas, radio frequency (RF) micro-electro-mechanical-systems (MEMS) based reconfigurable antennas, multifunctional antennas for 4G/5G communications and MIMO applications, metamaterials reconfigurable antennas, multifunctional antennas for user equipment (EUs), reconfigurable antennas for the defense applications and phased array antennas using 5G silicon RFICs.

The purpose of this book is to present in-depth theory, as well as design and development insight of these various multifunctional antennas and arrays. The book is aimed for use by practicing antenna engineers and researchers in the industry and academia. This book starts with an introduction to the antennas in Chapter 1, which discusses the importance of antennas. It also provides an introduction to antenna performance parameters, antenna types, multifunctional antennas, reconfigurable antennas, and antenna measurements. Next in Chapter 2, frequency reconfigurable antennas (FRAs) are detailed. This chapter starts with discussion of the mechanism of frequency reconfigurability, types of the FRAs using various switches and tunable components, FRAs by employing mechanical changes such as ground plane membrane deflection, and FRAs by using special materials and special shapes. Chapter 3 presents discussion on the pattern reconfigurable antennas which includes the following: pattern

reconfiguration by electronically changing antenna elements and feeding networks, mechanically controlled pattern reconfigurable antennas, pattern reconfigurable arrays and optimizations, and reconfigurable wearable and implanted antennas. In Chapter 4, we discuss the polarization reconfigurable antennas with emphasis on the polarization reconfiguration mechanism using RF switches, polarization reconfigurable antennas using solid-state RF switches, mechanical and micro-electro-mechanical-system (MEMS) RF switches, switchable feed networks, usage of metasurfaces, as well as other methods. These chapters describe the three main types of reconfigurable antennas and arrays as described in the introduction.

Reconfigurable antennas using the liquid metal, piezoelectric and RF MEMS are discussed in Chapter 5. This chapter specifically includes discussion on the liquid metal based frequency, pattern, and directivity reconfigurable antennas, piezoelectric based pattern reconfigurable arrays, and RF MEMS based frequency and pattern reconfigurable antennas. Compact reconfigurable antennas are discussed in Chapter 6 with the main focus on the reconfigurable pixel antennas, and reconfigurable antennas using fluidic, ferrite and magnetic materials, metamaterials and metasurfaces.

Reconfigurable MIMO antennas are presented in Chapter 7, which discusses the following: reconfigurable antennas for MIMO applications, isolation techniques in MIMO antennas, pattern diversity scheme, reconfigurable polarization MIMO antennas, MIMO antenna performance parameters, and finally some reconfigurable MIMO antenna examples. Chapter 8 offers discussion on the MIMO antennas in multifunctional systems, MIMO antennas in Radar systems, MIMO antennas in communication systems, MIMO antennas for sensing applications, MIMO antennas for 5G systems, massive MIMO arrays, dielectric lens for millimeter wave MIMO, beamforming in massive MIMO, MIMO in imaging systems, and MIMO antenna in medical applications. Use of metamaterials in reconfigurable antennas have been addressed in Chapter 9. This chapter focuses the discussion on metamaterials in antenna reconfigurability, metamaterial-inspired reconfigurable antennas, and metasurface-inspired reconfigurable antennas.

Chapter 10 provides detailed discussion on the multifunctional antennas for user equipments (UEs) with emphasis on the lower/sub-6 GHz 5G band antennas, 5G *mm*-wave antenna arrays, collocated sub-6 GHz and *mm*-Wave 5G array antennas, and RF and electromagnetic fields (EMF) exposure limits. The department of defense (DoD) related reconfigurable antennas are presented in Chapter 11 with a focus on the tactical air navigation system (TACAN) antennas, sea-based X-Band Radar 1 (SBX-1) antennas, the advanced multifunction RF concept (AMRFC) antennas, integrated topside (InTop) antennas, the Defense Advanced Research Projects Agency (DARPA) arrays of commercial timescales (ACT), and the Air Force Research Laboratory (AFRL) transformational element

level array (TELA). Finally, Chapter 12 discusses 5G silicon RFICs-based phased array antennas, which introduces silicon beamformer technology. It includes a short discussion of three phase shifting topologies using local oscillator (LO) based phase shifting, intermediate frequency (IF) based phase shifting and RF based phase shifting for beam steering array antennas. Several flat panel phased array antenna examples using the silicon beamforming chipsets both at Ku- and Ka-band with linear and circular polarizations are also presented.

We would like to mention that the slight overlap between the content in couple of chapters is acknowledged. We have done this intentionally so that discussion is complete in the respective chapters. While the contributors and authors have made great effort to present details for each topic area, they are by no means complete as the body of work in this field is large. They do represent the interpretations of each chapter's contributors. As time progresses, further improvements and innovations in the state-of-the-art technologies in reconfigurable antennas is anticipated. Therefore, it is expected that interested readers should continually refresh their knowledge to follow the growth of communication technologies.

1 February 2021
San Diego, CA, USA

Professor Satish K. Sharma, PhD
Jia-Chi S. Chieh, PhD

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Professor Satish K. Sharma will like to take this opportunity to thank his research collaborators, past and present graduate students, post-doctoral fellows, visiting scholars, and undergraduate students at San Diego State University (SDSU) who have been the continuous source for his research growth. He thanks Dr. Jia-Chi S. Chieh for agreeing to work on this book. He also thanks the funding agencies: National Science Foundation (NSF) for the prestigious CAREER award, the Office of Naval Research (ONR), the Naval Information Warfare Center-Pacific (NIWC-PAC), the Space and Naval Warfare Systems Command (SPAWAR)-San Diego, and the SBIR/STTR Phase I and II research grants subcontracted through the local industries, which have helped him pursue his research work. Finally, he thanks his spouse Mamta Sharma (Author and Artist) and daughters Shiva Shree Sharma (Doctoral Student in Material Science Engineering at University of California, Riverside, California) and Shruti Shree Sharma (Undergraduate Student in Electrical Engineering at University of California, Irvine, California) who spared their valuable time to let him work on this book and offered their unconditional love and support as always. He also thanks his pet dog and cat Charlie Sharma and Razzle Sharma, respectively, for their unconditional love to him. Lastly, he is grateful to his parents (Mr. Rama Naresh Sharma and Mrs. Taravati Sharma), elders in his extended family, research advisors (Professors L. Shafai, the University of Manitoba and B. R. Vishvakarma, Indian Institute of Technology, Banaras Hindu University), teachers, colleagues, friends and the almighty God for bestowing continuous blessings on him.

Dr. Jia-Chi S. Chieh is grateful to his research group at the Naval Information Warfare Center in San Diego for their tireless efforts in the development of low-cost phased array antennas over the last decade. He is also grateful for the research collaboration opportunities he has had with Prof. Satish K. Sharma from San Diego State University (SDSU), as well as his mentorship and friendship over the years. He is thankful to his family for their love and support, and who have allowed him to complete this work including his wife Kristine, and his two daughters Joanna and Audrey. Lastly, he is grateful to his parents (Dr. Shih-Huang Chieh and Mrs. Dolly Chieh), who taught him the importance of learning and to never stop.

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Professor Satish K. Sharma, PhD
Jia-Chi S. Chieh, PhD

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San Diego, CA, USA

Professor Satish K. Sharma, PhD
Jia-Chi S. Chieh, PhD

1

Introduction

Satish K. Sharma and Jia-Chi S. Chieh

1.1 Introduction

In this chapter, we provide basic discussion about an antenna and its importance, type of antennas, and introductory information about the reconfigurable antenna, frequency agile antenna, multifunctional antenna, and antenna measurements.

1.2 Antenna: an Integral Component of Wireless Communications

An antenna is described as a device that radiates or receives transverse electromagnetic waves (TEM) from its surface, or structure. It is an integral component of all the wireless communication systems. As shown in Figure 1.1, the transmitter block which usually consists of the signal generator, modulator, and power amplifiers is terminated with an antenna to radiate the power in free space. A poor choice and design of antenna will result in the power being reflected to the source and cause waste of power, which is undesirable. Efficient power utilization becomes critical in applications such as onboard circuits in satellite communications. To emphasize the importance of antennas for the receiver circuitry, maximum power should be obtained from the incident wave to relax the burden on the succeeding blocks such as low noise amplifiers to maintain the required signal-to-noise-ratio (SNR) for satisfactory wireless links. Different communication application demands different minimum required SNR for a satisfactory link and efficient antenna design plays a big role in achieving this goal.

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Figure 1.1 The importance of antenna in a wireless communication system.

1.3 Antenna Performance Parameters

Antenna performance parameters can be categorized into two groups: circuit parameters and radiation parameters. Circuit parameters refer to the impedance matching properties such as reflection coefficient magnitudes ($|S_{ii}|$) and isolation ($|S_{ij}|$) between the antenna ports. Antenna radiation parameters refer to radiation patterns, gain, directivity, antenna efficiency, polarization, effective length and effective aperture, antenna temperature, etc. Readers should refer to the well-known text book by C. A. Balanis, *Antenna Theory: Analysis and Design* (Fourth Revised edition), Wiley publications [1] for detailed discussion and learning about these antenna performance parameters.

1.4 Antenna Types

Various antennas that find use in wireless communication systems can be classified in many ways. Antenna geometry of four selected antennas is shown in Figure 1.2. Figure 1.2a shows a well-known bow-tie planar antenna that is known for wideband operation with omnidirectional radiation pattern performance. A planar inverted F-antenna (PIFA) is shown in Figure 1.2b which has been known to provide single and multi-band operation based on suitable dimension of the radiating structures and feeding mechanism. It also offers omnidirectional radiation patterns. Figure 1.2c shows a quasi-Yagi planar antenna which offers end-fire directional radiation patterns. Similarly, Figure 1.2d shows a stepped Vivaldi planar antenna which is known for its extremely wideband antenna performance.

The antenna performance can be characterized using impedance matching and radiation patterns. One example is shown in Figure 1.3. Figure 1.3a shows reflection coefficient magnitude versus frequency and Figure 1.3b shows 3D gain radiation patterns of an antenna. There are numerous full-wave analysis tools, also called Maxwell Solvers, which provide accurate simulation and analysis results for an antenna. One such tool is Ansys high-frequency structure simulator (HFSS) which has been used to generate these impedance matching and radiation pattern.

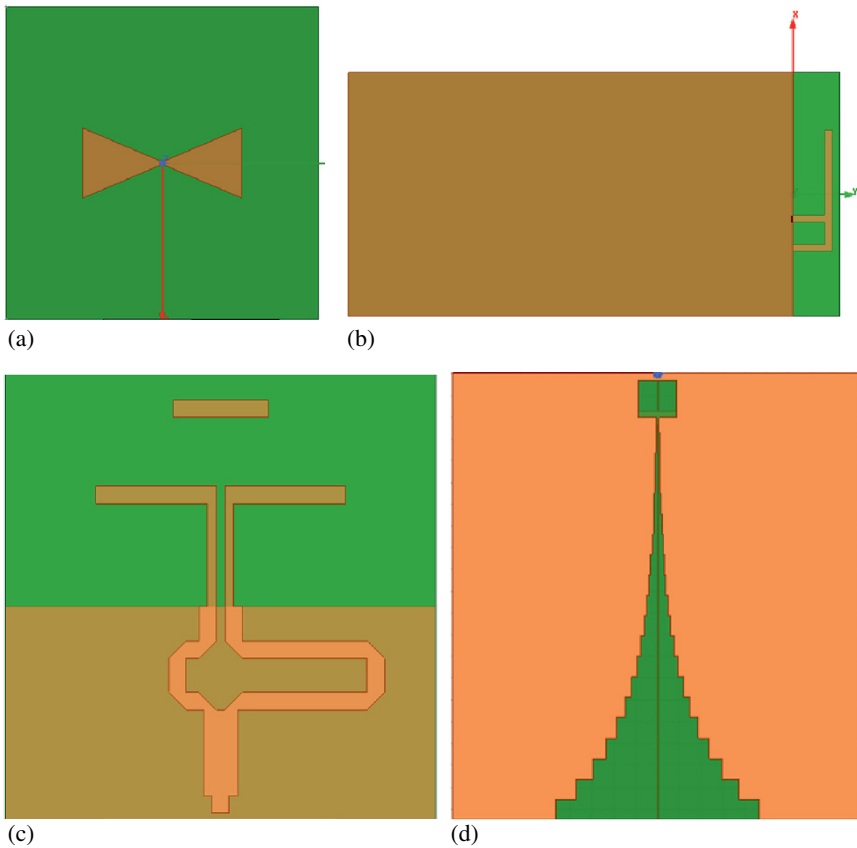


Figure 1.2 Some antenna types generated through Antenna Design Kit in Ansys Electronic Package.

1.5 Multifunctional Antennas

Multifunctional antennas can have features of frequency reconfiguration, polarization reconfiguration, beam steering, flexible radiation patterns, and radiation pattern reconfiguration in a single antenna structure. Combination of a couple of these features makes these antennas “multifunctional.” These antennas can meet multiple wireless communication standards and hence can provide multiple communication applications. Such antennas can also be multiband in nature and can have multiple-input-multiple-output (MIMO) implementations. Also, multiple

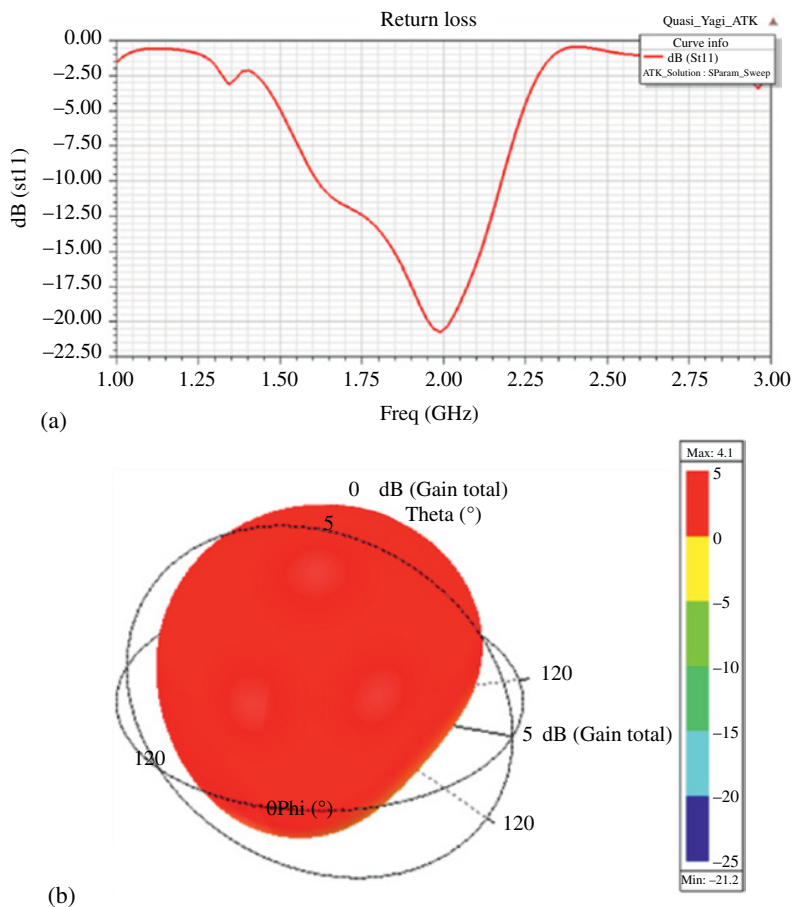


Figure 1.3 Antenna performance shown using (a) reflection coefficient magnitude (S_{11} , dB) and (b) 3D gain radiation pattern.

communication antennas on a common small size host platform, such as cellular phone size ground plane, can be categorized as “multifunctional” antenna.

The full-polarization reconfigurable antenna can switch between the vertical and horizontal linear polarizations, right-hand circular polarization (RHCP), and left-hand circular polarization (LHCP) depending on the communication system requirements. These antennas offer advantages of reduced antenna hardware, low weight, and low cost. Such antennas are very attractive to emerging wireless communications such as 5G communication systems. One such antenna

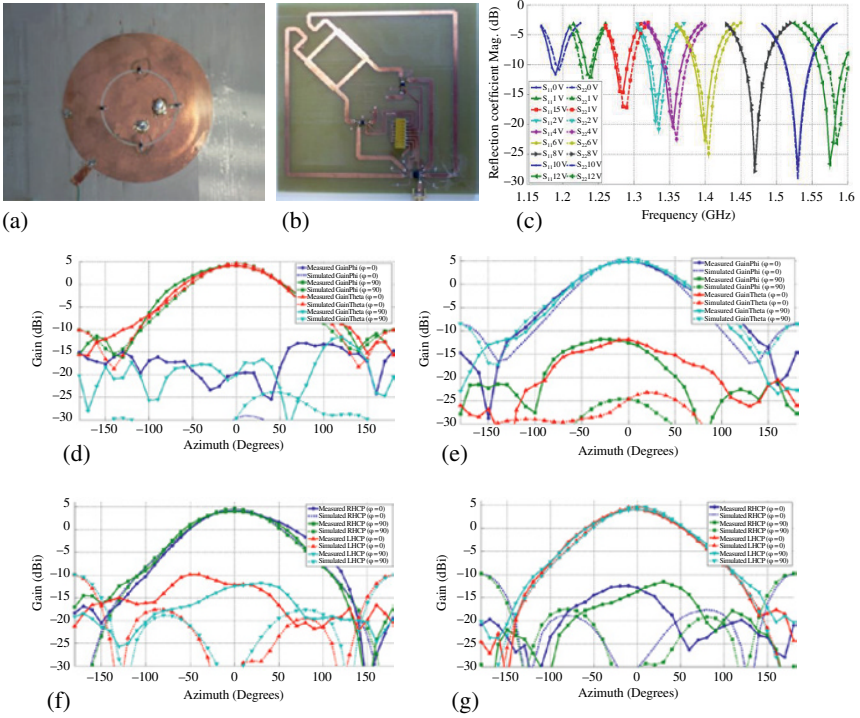


Figure 1.4 (a) Top view photograph of a frequency tunable concentric circular microstrip patch antenna along with varactor diode placement locations, (b) photograph of the fabricated control feed network, (c) measured frequency tunable response for both feed ports, and (d–g) comparison between the measured and simulated gain radiation patterns for 4V bias voltage which corresponds to 1.36 GHz tunable band for horizontal linear, vertical linear, RHCP, and LHCP, respectively. *Source:* Babakhani and Sharma [2].

is shown in Figure 1.4, which offers both frequency tunability and polarization reconfiguration [2].

Tunable antennas, mostly, frequency tunable can be designed by incorporating variable capacitors in a radiating element in suitable placement arrangements. Figure 1.4a shows photograph of a prototype frequency tunable concentric circular patch antenna where four varactors (Skyworks SMV 1234) are placed between the central patch and the outer ring patch. Two feed ports are selected so that both linear and circular polarizations can be obtained by suitably exciting feed points. Figure 1.4b shows photograph of the control feed network which provides polarization reconfiguration along with simultaneously frequency tunability. The control feed network uses single pole double through (SPDT) and single pole 4 through (SP4T) RF switches along with quadrature power divider, dual in package

(DIP) switch, and control lines for biasing varactor diodes and RF switches. A DIP switch is included to apply DC voltage to control the state of the switches. To bias the varactors for tunability, the central patch is connected to the positive pole through the feed network circuit. For the radiation pattern measurements in the anechoic chamber, varactor diodes were biased with a Jameco Electronics DC–DC Boost Converter.

The frequency response with bias voltage variation is shown in Figure 1.4c. With 0V bias, the antenna resonates at the lowest frequency (1.17 GHz). Similarly, with 12V bias, the antenna operates at 1.58 GHz. Thus, this antenna provides frequency tunability between 1.17 and 1.58 GHz which corresponds to 30% tunability. By applying bias voltage to two varactors each along with one feed point, vertical and horizontal linear polarizations are achieved. Similarly, applying the same bias voltage to all the varactors and exciting both feed points in $\pm 90^\circ$ time phase difference, right hand (RH) or left hand (LH) circular polarization is obtained. Measured and simulated radiation patterns are shown in Figure 1.4d–g for 1.36 GHz (4V bias) for all four polarization cases. Similar was the pattern response for all other frequency tunable bands but are not shown for the sake of brevity.

1.6 Reconfigurable Antennas

Reconfigurable antennas can be frequency reconfigurable, pattern reconfigurable, or polarization reconfigurable or combination of these types. Once again, reconfigurable antennas can be categorized as a multifunctional antenna in general like the one discussed in the Section 1.5. Reconfiguration is obtained by varying the antenna structure with the help of RF or optical switches. One such antenna demonstrating frequency reconfiguration is shown in Figure 1.5.

The geometry of the proposed PIFA element is shown in Figure 1.5a and b. This miniaturized antenna is able to achieve consistent high band coverage while reconfigurable lower frequency bands are maintained. The antenna is matched across all the 4G/LTE lower reconfigurable bands and simultaneous higher consistent wireless bands. The antenna miniaturization and impedance matching are possible by exploiting the meandering and mutual coupling between the different parts of the antenna structure. It employs ground plane edge effect for its optimum performance.

The reconfigurable antenna element (Figure 1.5a, b) is designed by using Ansys HFSS on a tablet size ground plane of $L_4 = 180$ mm and $W_4 = 150$ mm [3, 4]. The corresponding antenna dimensions are: length arm, $L_1 = 73$ mm and width, $W_1 = 2.3$ mm to the first PIN diode switch, and second ground extension, $L_2 = 20$ mm with end width, $W_2 = 7$ mm, coupling grounding gap, $g = 5.6$ mm and $g_1 = 3.8$ mm designed on a FR4 ($\epsilon_r = 4.4$, $\tan \delta = 0.021$) substrate with thickness,

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