# Adaptive Array Systems

## Fundamentals and Applications

**B. Allen and M. Ghavami**

*Both of*
*Centre for Telecommunications Research*
*King's College London, UK*

**John Wiley & Sons, Ltd**

# Adaptive Array Systems

# Adaptive Array Systems

## Fundamentals and Applications

**B. Allen and M. Ghavami**

*Both of*
*Centre for Telecommunications Research*
*King's College London, UK*

**John Wiley & Sons, Ltd**

 John Wiley & Sons Ltd,
The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk

Visit our Home Page on www.wiley.com



**Other Wiley Editorial Offices**

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 33 Park Road, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

**British Library Cataloguing in Publication Data**

A catalogue record for this book is available from the British Library

ISBN 0-470-86189-4

Typeset by the authors using LaTeX software.
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire.
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

# *Contents*

# *Preface*

## Readership

Firstly, this book is set at a level suitable for senior undergraduate and postgraduate students who wish to understand the fundamentals and applications of adaptive array antenna systems. Array fundamentals are described in the text, and examples which demonstrate theoretical concepts are included throughout the book, as well as summaries and questions at the end of each chapter. We also consider this book to be useful for researchers, practising engineers and managers alike, especially where an accessible text on adaptive array fundamentals and applications is required. A complete chapter on implementation aspects highlights the challenges a designer may encounter during the development of an array system. The book contains explanations of fundamentals, description of algorithms and presentation of research-based case studies making it appeal to a wide readership.

## About the Book

This book aims to provide an accessible text on adaptive array fundamentals. Although the book considers a wide range of applications, including wireless communications, radar, sonar and bio-medical, the focus is predominantly wireless communications. This reflects the research interests of the authors, but it should

be noted that many of the techniques introduced throughout the text can be applied to other branches of engineering such as bio-medical.

The book is structured as follows. Chapter 1 (Fundamentals of Array Signal Processing) introduces antenna and sensor terminology and then discusses common antenna elements and reviews the characteristics of each. The chapter concludes by reviewing the array system concept. In chapter 2 (Narrowband Array Systems), the behaviour of narrowband antenna arrays is analysed. The function of phase and amplitude weights and beamsteering is explored within the context of a narrowband array, and the phenomenon of grating lobes is introduced. The chapter concludes by characterising a number of common window functions that are used to control the sidelobe levels of array beam-patterns. Chapter 3 (Wideband Array Processing) then introduces and analyses several wideband beamforming techniques and compares the performance of each. The focus of chapter 4 (Adaptive Arrays) is on algorithms, where a range of adaptive algorithms and direction of arrival algorithms are presented and discussed. The chapter concludes with a review of several blind beamforming algorithms and a comparison of direction of arrival estimation performance. Chapter 5 (Practical Considerations) contains a wide variety of topics that relate to implementation aspects of adaptive arrays. These include hardware implementation aspects, circular arrays, channel modelling and transmit beamforming. Finally, chapter 6 (Applications) discusses the application of adaptive array systems through several detailed case studies on:

- wideband arrays, radar, sonar and bio-medical imaging;
- second- and third-generation terrestrial wireless systems; and
- satellite communication systems.

Several texts already exist on adaptive arrays as it is a topic that has undergone significant research and development over the last 50 years. These texts can be broadly classified as follows:

- rigorous mathematical treatment;
- emphasis on radar; and
- emphasis on wireless communications.

In contrast to many of these texts, we have tried to make this book readable and accessible to the uninitiated, with a broad range of applications considered and full chapters covering wideband beamforming and implementation aspects. We have also included research-based material making it appeal to the experienced researcher as well.

Some consider adaptive antennas to be a mature technology with little research left to tackle. Contrary to this belief, we consider there to be an ongoing interest in adaptive antennas for future (3G and 4G) mobile communications systems,

ultra wideband (UWB) wireless systems where the signal bandwidth is very large, and satellite communication and navigation systems. In particular, UWB presents many research challenges in the area of communications and bio-medical engineering and the applications of antenna arrays can provide performance gains to both.

We consider this text to be unique because it covers array fundamentals for a wide range of applications, as well as specifically covering implementation aspects and applications through detailed case studies. Examples are included throughout the text which illustrate the concepts under discussion and we have attempted to write the text in an accessible and appealing way.

### Prerequisites

In order for the most to be gained from the contents of this book, it is recommended (but not essential) that the reader has a firm grounding in the principles of:

- engineering mathematics, including Fourier analysis and matrix algebra;
- signals and systems;
- electromagnetics;
- radiowave propagation;
- radio frequency circuit design; and
- communications engineering principles.

### Course Design

This book has been designed in such a way that it forms a complete semester's course on adaptive array systems. We suggest that such a self-contained course consists of four-hours of lectures and a two-hour tutorial for each chapter, with actual times being adjusted according to ability. In particular, chapters 1 and 2 present the fundamentals of radiation, antenna elements and beamforming suitable for taught courses, and chapter 4 contains fundamental signal processing concepts for adaptive arrays. These topics can be complemented with implementation issues and case studies in chapters 5 and 6. In contrast, chapter 3 is particularly suited for the research-active readership, as is substantial sections of chapters 5 and 6 where novel developments are reported, especially with regard to wideband beamforming algorithms and channel modelling.

As an extra resource, the companion website for our book contains a solutions manual, Matlab m-files for the examples and problems, and a sample chapter.

Also, for those wishing to use this material for lecturing purposes, electronic versions of some of the figures are available. Please go to the following URL and take a look: ftp://ftp.wiley.co.uk/pub/books/allen.

We hope that you find this book useful both as a reference, a learning tool and a stepping stone to further your own efforts in this multi-disciplinary field of engineering.

B. Allen
M. Ghavami

London

# *Acknowledgments*

Our thanks are extended to our colleagues at the Centre for Telecommunications Research, King's College London for providing a rich research environment that has enabled the timely development of this book. In particular, we wish to thank Professor Hamid Aghvami for his leadership and provision of opportunity. Also, we especially thank Dr Mischa Dohler, Neville Tyler, Adil Shah and Dora Karveli for contributing to this book. Without these contributions the book would not have reached its current form. Thank you!

The authors wish to express their gratitude to Professors Joe McGeehan, Andy Nix, Mark Beach, and Dr Geoff Hilton of the University of Bristol, who have conducted substantial research into adaptive antenna systems that has aided in the formulation of this book. In particular, we wish to thank Professor Mark Beach for reviewing this book and Ben wishes to thank him for his expert PhD supervision that has provided invaluable inspiration.

Our gratitude goes to the IEEE and IEICE for granting permission to incorporate substantial sections of published works in chapters 3 and 6. We would also like to thank Sarah Hinton at Wiley for assisting with the organisation, marketing and production of this book, and to the anonymous copy editor for the attention to detail that was evident in the corrections.

Last, but certainly not least, Ben wishes to thank:

> his wife, Louisa, for her love and companionship during the last few years, during which a wide variety of challenges have been faced by us. He also wishes to dedicate this book to Louisa and his ancestors: Leslie (Bill) Allen

and William Smith who spent their working lives involved with early telecommunications technologies.

and Mohammad wishes to thank:

his wife, Mahnaz, and children for their love and patience during the period of preparation for this book. Mohammad would like to dedicate this book in memory of his father, Reza.

# *List of Figures*