Waveform Design for Active Sensing Systems

A Computational Approach

With a focus on developing computational algorithms for examining waveform design in diverse active sensing applications, this guide is ideal for researchers and practitioners in the field. The three parts conveniently correspond to the three categories of desirable waveform properties: good aperiodic correlations, good periodic correlations and beampattern matching. The book features various application examples of using the newly designed waveforms, including radar imaging, channel estimation for communications, an ultrasound system for breast cancer treatment and covert underwater communications. In addition to numerical results, the authors present theoretical analyses describing lower bounds or limitations of performance. Focusing on formulating practical problems mathematically and solving the mathematical problems using efficient and effective optimization techniques, the text pays particular attention to developing easy-to-use computational approaches. Most algorithms are accompanied by a table clearly detailing iteration steps, and corresponding MATLAB codes are available on the companion website.

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Preface

The focus of this book is on developing computational algorithms for transmit waveform design in active sensing applications, such as radar, sonar, communications and medical imaging. Waveforms are designed to achieve certain desired properties, which are divided into three categories corresponding to the three main parts in the book, namely good aperiodic correlations, good periodic correlations and beampattern matching. The principal approach is based on formulating practical problems mathematically and then solving the problems using optimization techniques. Particular attention is paid to making the developed algorithms computationally efficient. Theoretical analysis that describes performance lower bounds or limitations is provided. Various application examples using the newly designed waveforms are presented, including radar imaging, channel estimation, an ultrasound system for medical treatment and covert underwater spread spectrum communications.

This book is a research monograph. Its backbone is a series of innovative waveform-design algorithms that we have developed in recent years. These algorithms address different specific problems of waveform design, yet the topics discussed are all centered around active sensing applications and the optimization techniques share similar ideas (e.g., iterative and cyclic procedures, incorporation of fast Fourier transforms, etc.). Notably, all these algorithms are computational approaches that reply on the implementation of computer programs, as opposed to classic waveform design approaches that are mostly analytical. By stitching these algorithms together in a book, we are able to tell a detailed story on various aspects of waveform design, within a consistent framework highlighting computational approaches.

The subject matter of this book falls into the field of electrical engineering, more specifically, into the area of signal processing. The main targeted readers are researchers as well as practitioners in industry who are interested in signal design for radar, sonar and communication systems. We have made a significant effort to present the algorithms in a rigorous and self-contained way, so that interested readers can learn the new waveform-design framework thoroughly. Besides newly developed algorithms, a considerable portion of the book presents tutorial-like materials; for example, we review existing waveforms, analyze properties of ambiguity functions and describe application scenarios. Little background knowledge is required beyond a basic understanding of signal processing and linear algebra. Therefore the book can also serve as an introduction to waveform design for active sensing applications. Readers can access demonstration

MATLAB programs that cover many examples illustrated in the book via the dedicated website http://www.sal.ufl.edu/book/.

Following Chapter 1, which contains an introduction, the other chapters are structured into four parts. In Part I (Chapters 2 to 8) we discuss *aperiodic* sequence design. The heart of the discussion is to achieve desired correlation properties for a single sequence or a sequence set. Revolving around the correlation concept, other topics discussed include frequency stopbands, ambiguity functions and receiver design. In Part II (Chapters 9 to 12) we discuss *periodic* sequence design, and this largely parallels the first four chapters of Part I. In Part III (Chapters 13 to 15) we describe array beampattern synthesis. Finally, in Part IV (Chapters 16 to 19) we study several application examples where the newly developed waveforms lead to an improved performance.

Research on waveform design has thrived since the 1950s, following a number of pioneering works such as Shannon's communication theory and Woodward's ambiguity function. A vast amount of literature has been devoted to this area. As such, we do not attempt to cover every aspect of it. In fact, most discussion in this book is limited to phase-coded waveforms and the correlation-related properties thereof, and this by no means represents all waveform models or application scenarios for active sensing. However, by focusing on modern computational methods we hope to bring in a new methodology and contribute from a perspective that is different from classic methods. It is conceivable that advances in computing power and optimization techniques will continue to herald new and improved approaches to waveform design.

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Notation

j	the imaginary unit; $j^2 = -1$
a^*	complex conjugate of scalar a
$\mathrm{Re}(a)$	real part of scalar a
$\mathrm{Im}(a)$	imaginary part of scalar a
$\|\|\mathbf{a}\|\|$	Euclidean norm of vector $\mathbf{a}$
$\mathbf{A}^*$	complex conjugate of matrix $\mathbf{A}$
$\mathbf{A}^T$	transpose of matrix $\mathbf{A}$
$\mathbf{A}^H$	conjugate transpose of matrix $\mathbf{A}$
$\mathrm{tr}(\mathbf{A})$	trace of matrix $\mathbf{A}$
$\|\|\mathbf{A}\|\|$	Frobenius norm of matrix $\mathbf{A}$
$\mathbf{A} \odot \mathbf{B}$	Hadamard (element-wise) product of two matrices
$\mathbf{A} \geq 0$	matrix $\mathbf{A}$ is positive semidefinite
$\mathbf{A} \leq \mathbf{B}$	matrix $\mathbf{B} - \mathbf{A}$ is positive semidefinite
δ_n	Kronecker delta; $\delta_n = 1$ if $n = 0$ and $\delta_n = 0$ otherwise
δ_{mn}	an extension of δ_n; $\delta_{mn} = 1$ if $m = n$ and $\delta_{mn} = 0$ otherwise
$\mathbf{I}_M$	identity matrix of dimension $M \times M$
$f(x) * g(x)$	convolution of two functions $f(x)$ and $g(x)$
$\lfloor x \rfloor$	largest integer less than or equal to (real-valued) x
$\arg(x)$	phase angle (in radians) of x

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Abbreviations

AF	ambiguity function
BER	bit error rate
CA	cyclic algorithm
CAF	cross AF
CAN	cyclic algorithm-new
CIR	channel impulse response
CREW	cognitive receiver and waveform (design)
DFT	discrete Fourier transform
FFT	fast Fourier transform
ISL	integrated sidelobe level
IV	instrumental variable
MF	merit factor
MIMO	multi-input multi-output
MSE	mean-squared error
Multi-CAN	multi-sequence CAN
Multi-CAO	multi-sequence CA original
Multi-PeCAN	multi-sequence PeCAN
Multi-PeCAO	multi-sequence periodic CA original
Multi-WeCAN	multi-sequence WeCAN
PAF	periodic AF
PAR	peak-to-average power ratio
PeCAN	periodic CAN
PSL	peak sidelobe level
SAR	synthetic aperture radar
SCAN	stopband CAN
SNR	signal-to-noise ratio
UWA	underwater acoustic
WB-CA	wideband CA
WeCAN	weighted CAN
WeSCAN	weighted SCAN
WISL	weighted ISL
ZCZ	zero-correlation zone

