AUTOMATIC MODULATION CLASSIFICATION

PRINCIPLES, ALGORITHMS AND APPLICATIONS

ZHECHEN ZHU
ASOKE K. NANDI

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Automatic Modulation Classification

Principles, Algorithms and Applications

Zhechen Zhu and Asoke K. Nandi

Brunel University London, UK

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To
Xiaoyan and Qiaonan Zhu
Marion, Robin, David, and Anita Nandi

About the Authors

Zhechen Zhu received his B.Eng. degree from the Department of Electrical Engineering and Electronics at the University of Liverpool, Liverpool, UK, in 2010. Before graduating from the University of Liverpool, he also studied in Xi'an Jiaotong-Liverpool University, People's Republic of China for two years. He recently submitted his thesis for the degree of PhD to the Department of Electronic and Computer Engineering at Brunel University London, UK. Since 2009, he has been working closely with Professor Asoke K. Nandi on the subject of automatic modulation classification. Their collaboration has made an important contribution to the advancement of automatic modulation classification in complex channels using modern machine learning techniques. His work has since been published in three key journal papers and reported in several high quality international conferences.

Asoke K. Nandi joined Brunel University London in April 2013 as the Head of Electronic and Computer Engineering. He received a PhD from the University of Cambridge, UK, and since then has worked in many institutions, including CERN, Geneva; University of Oxford, UK; Imperial College London, UK; University of Strathclyde, UK; and University of Liverpool, UK. His research spans many different topics, including automatic modulation recognition in radio communications for which he received the Mountbatten Premium of the Institution of Electrical Engineers in 1998, machine learning, and blind equalization for which he received the 2012 IEEE Communications Society Heinrich Hertz Award from the Institute of Electrical and Electronics Engineers (USA).

In 1983 Professor Nandi was a member of the UA1 team at CERN that discovered the three fundamental particles known as W^+, W^- and Z^0, providing the evidence necessary for the unification of the electromagnetic and weak forces, which was recognized by the Nobel Committee for Physics in 1984. He has been honoured with the Fellowship of the Royal Academy of Engineering (UK) and the Institute of Electrical and Electronics Engineers (USA). He is a Fellow of five other professional institutions, including the Institute of Physics (UK), the Institute of Mathematics and its Applications (UK), and the British Computer Society. His publications have been cited well over 16 000 times and his *h*-index is 60 (Google Scholar).

Preface

Automatic modulation classification detects the modulation type of received signals to guarantee that the signals can be correctly demodulated and that the transmitted message can be accurately recovered. It has found significant roles in military, civil, intelligence, and security applications.

Analogue Modulations (e.g., AM and FM) and Digital Modulations (e.g., PSK and QAM) transform baseband message signals (of lower frequency) into modulated bandpass signals (of higher frequency) using a carrier signal for the purpose of enhancing the signal's immunity against noise and extending the transmission range. Different modulations require different hardware configurations and bandwidth allocations. Meanwhile, they provide different levels of noise immunity, data rate, and robustness in various transmission channels. In order to demodulate the modulated signals and to recover the transmitted message, the receiving end of the system must be equipped with the knowledge of the modulation type.

In military applications, modulations can serve as another level of encryption, preventing receivers from recovering the message without knowledge of the modulation type. On the other hand, if one hopes to recover the message from a piece of intercepted and possibly adversary communication signal, a modulation classifier is needed to determine the modulation type used by the transmitter. Apart from retrieving the transmitted message, modulation classification is also useful for identifying the transmitting unit and to generate jamming signals with matching modulations. The process is initially implemented manually with experienced signal engineers and later automated with automatic modulation classification systems to extend the range of operable modulations and to improve the overall classification performance.

In modern civilian applications, unlike in much earlier communication systems, multiple modulation types can be employed by a signal transmitter to control the data rate, to control the bandwidth usage, and to guarantee the integrity of the message. Though the pool of modulation types is known both to transmitting and receiving ends, the selection of the modulation type is adaptive and may not be known at the receiving end. Therefore, an automatic modulation classification mechanism is required for the receiving end to select the correct demodulation approach in order to guarantee that the message can be successfully recovered.

This research monograph covers different algorithms developed for the automatic classification of communications signal modulation types. The theoretical signal models are explained in the first two chapters to provide the principles on which the analyses are based. An important step is to unify various signal models proposed in different studies and to provide a common framework for analysis of different automatic modulation classification algorithms.

This book includes the majority of the methods developed over the last two decades. The algorithms are systematically classified to five major categories: likelihood-based classifiers, distribution test-based classifiers, feature-based classifiers, machine learning-assisted classifiers, and blind modulation classifiers. For each type of automatic modulation classifier, the assumptions and system requirements are listed, and the design and implementation are explained through mathematical expressions, graphical illustrations and programming pseudo codes. Performance comparisons among several automatic modulation classifiers from each category are presented with both theoretical analysis and simulated numerical experiments. MATLAB® source code of selected methods will be available on https://code.google.com/p/amc-toolbox/.

The accumulated knowledge on the principle of automatic modulation classification and the characteristics of different automatic modulation classification algorithms is used to suggest the detailed implementation of modulation classifiers in specific civilian and military applications.

As the field is still developing, such a book cannot be definitive or complete. Nonetheless it is hoped that graduate students should be able to learn enough basics before studying journal papers; researchers in related fields should be able to get a broad perspective on what has been achieved; and current researchers as well as engineers in this field should be able to use it as a reference.

A work of this magnitude will unfortunately contain errors and omissions. We would like to take this opportunity to apologise unreservedly for all such indiscretions in advance. We welcome any comments or corrections; please send them by email to a.k.nandi@ieee.org or by any other means.

Zhechen Zhu and Asoke K. Nandi
London, UK

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List of Abbreviations

AD	Anderson–Darling
ALRT	Average likelihood ratio test
AM	Amplitude modulation
AMC	Automatic modulation classification
AM&C	Adaptive modulation and coding
ANN	Artificial neural network
ASK	Amplitude-shift keying
AWGN	Additive white Gaussian noise
BMC	Blind modulation classification
BP	Back propagation
BPL	Broadband over power line
BPSK	Binary phase-shift keying modulation
CDF	Cumulative distribution function
CDP	Cyclic domain profile
CSI	Channel state information
CvM	Cramer–von Mises
CWT	Continuous wavelet transform
DFT	Discrete Fourier transform
DLRT	Discrete likelihood ratio test
DSB	Double-sideband modulation
DSSS	Direct sequence spread frequency
EA	Electronic attack
ECDF	Empirical cumulative distribution function
ECM	Expectation/condition maximization
EM	Expectation maximization
EP	Electronic protect
ES	Electronic support
EW	Electronic warfare
FB	Feature-based
FHSS	Frequency-hopping spread spectrum

FM	Frequency modulation
FSK	Frequency-shift keying
GA	Genetic algorithm
GLRT	Generalized likelihood ratio test
GMM	Gaussian mixture model
GoF	Goodness of fit
GP	Genetic programming
HLRT	Hybrid likelihood ratio test
HoS	High-order statistics
ICA	Independent component analysis
I-Q	In-phase and quadrature
KNN	K-nearest neighbour
KS	Kolmogorov–Smirnov
LA	Link adaptation
LB	Likelihood-based
LF	Likelihood function
LPD	Low probability of detection
LSB	Lower sideband modulation
LUT	Lookup table
MAP	Maximum a posteriori
MDLF	Minimum distance likelihood function
MIMO	Multiple-input and multiple-output
ML	Maximum likelihood
MLP	Multi-layer perceptron
MSE	Mean squared error
M-ASK	M-ary amplitude shift keying modulation
M-FSK	M-ary frequency shift keying modulation
M-PAM	M-ary pulse amplitude modulation
M-PSK	M-ary phase-shift keying modulation
M-QAM	M-ary quadrature amplitude modulation
ML-M	Magnitude-based maximum likelihood classifier
ML-P	Phase-based maximum likelihood classifier
NPLF	Non-parametric likelihood function
ODST	Optimized distribution sampling test
PAM	Pulse amplitude modulation
PD	Phase difference
PDF	Probability density function
PM	Phase modulation
PSK	Phase-shift keying modulation
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase-shift keying modulation

SC	Spectral coherence
SCF	Spectral correlation function
SISO	Single-input and single-output
SM	Spatial multiplexing
SNR	Signal-to-noise ratio
SSB	Single-sideband modulation
STC	Space-time coding
SVM	Support vector machine
SαS	Symmetric alpha stable
USB	Upper sideband modulation
VSB	Vestigial sideband modulation

List of Symbols

A	Modulation alphabet
H	Channel matrix
h	Channel coefficient
I	In-phase segment
L	Number of signal realizations
N	Number of samples / signal length
Q	Quadrature segment
P_{cc}	Classification accuracy
$\boldsymbol{r}$	Received signal
$\boldsymbol{s}$	Transmitted signal
W	Bandwidth
w	Weight
$\mathfrak{I}$	Imaginary component
$\mathfrak{M}$	Candidate modulation pool
$\mathfrak{R}$	Real component
Θ	Channel parameter set
Λ	Likelihood ratio
σ^2	Signal variance
ω	Additive noise
$\mathcal{H}$	Hypothesis model
$\mathcal{L}$	Likelihood
$\log \mathcal{L}$	Log-likelihood
$\mathcal{M}$	Modulation
$\mathbb{F}$	Modulation classification feature
$\boldsymbol{\mathbb{F}}$	Modulation classification feature set

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