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OFDM

for Underwater Acoustic Communications

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OFDM FOR UNDERWATER ACOUSTIC COMMUNICATIONS

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To Juanjuan, Daniel, Joyce, and my parents Heting and Caiyun
S. Z.

To my parents Yongcheng and Jiuqin
Z.-H. W.

Preface

Underwater acoustic (UWA) channels have been regarded significantly different from wireless radio channels, due to their unique characteristics, such as large temporal variations, abundance of transmission paths, and wideband property in nature. Although there are a plethora of digital and wireless communication textbooks, most of them are tailored towards wireless radio channels, where simplified channel models are usually adopted to streamline presentation. Following standard receiver designs in textbooks, a practitioner might often be frustrated by the receiver performance in real underwater acoustic environments. This book is written to unfold and to address the challenges in UWA communications particularly for the multicarrier modulation in the form of orthogonal frequency-division multiplexing (OFDM).

The last decade has witnessed the tremendous development and revolutionary impact of OFDM on high data-rate radio communications. It is the workhorse of many wireless communication standards, such as WiFi (IEEE 802.11 a/g/n), WiMAX (IEEE 802.16), digital audio and video broadcasting (DAB/DVB), and the fourth generation (4G) cellular systems. The popularity of OFDM stems from its capability to convert a long multipath channel in the time domain into multiple parallel single-tap channels in the frequency domain, thus considerably simplifying receiver design. Such a feature makes OFDM an attractive choice for UWA channels. However, the feasibility of underwater acoustic OFDM had not been validated with experimental data sets until the mid 2000s, although OFDM has been tested in UWA environments since the 1990s. Considerable progress for OFDM has been observed in the UWA community since the late 2000s.

This book is dedicated to the techniques for OFDM in UWA channels, and different chapters are focused on addressing different challenges. Readers are expected to have certain signal processing and communication background. For readers within the UWA community, this book could deepen their understanding in the design aspects specific to underwater systems. For readers outside the UWA community, this book will help them to appreciate the distinctions of system design in different domains.

The technical content of this book mainly originates from the research performed within the UnderWater Sensor Network (UWSN) lab at the University of Connecticut (UCONN), which is co-directed by Dr. Jun-Hong Cui and the first author Dr. Shengli Zhou. The past and existing members who have contributed to the content of the book include: postdoctoral researchers: Drs. Jie Huang, Hao Zhou, and Xiaoka Xu; past Ph.D. students: Drs. Baosheng Li, Christian Berger, Jianzhong Huang; current Ph.D. students: Patrick Carroll, Lei Wan, Yi Huang; past M.S. students: Sean Mason, Weian Chen, Wei Zhou; and visiting scholars: Yougan Chen,

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Last but not least, we are grateful to our family members for their continuous support and encouragement throughout the project.

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Acronyms

AF	Amplify and Forward
ANC	Analogy Network Coding
AoA	Angle of Arrival
ARQ	Automatic Repeat Request
AUTEC	Atlantic Undersea Test and Evaluation Center
AUV	Autonomous Underwater Vehicle
BCJR	The Bahl-Cocke-Jelinek-Raviv Algorithm
BICM	Bit Interleaved Coded Modulation
BP	Basis Pursuit
BPSK	Binary Phase-Shift Keying
BER	Bit Error Rate
BLER	Block Error Rate
CC	Convolutional Code
CCDF	Complementary Cumulative Distribution Function
CCI	Cochannel Interference
CDF	Cumulative Distribution Function
CDMA	Coded-Division Multiple Access
CF	Compress and Forward
CFO	Carrier Frequency Offset
CP	Cyclic Prefix
CRLB	Cramer-Rao Lower Bound
CS	Compressive Sensing
CSI	Channel State Information
CZT	Chirp Z-Transform
DBC	Dynamic Block-Cycling
DCC	Dynamic Coded Cooperation
DF	Decode and Forward
DFE	Decision-Feedback Equalization
DFT	Discrete Fourier Transform
DSSS	Direct Sequence Spread Spectrum
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FH	Frequency Hopping
FG	Factor Graph

FSK	Frequency Shift Keying
GIB	GPS Intelligent Buoy
GLRT	Generalized Log-Likelihood Test
GMP	Gaussian Message Passing
GPS	Globe Positioning System
HFM	Hyperbolic-Frequency Modulation
IBI	Interblock Interference
ICI	Intercarrier Interference
i.i.d.	Independent and Identically Distributed
IMM	Interacting Multiple Model
ISI	Intersymbol Interference
LASSO	Least Absolute Shrinkage and Selection Operator
LBL	Long Baseline
LDPC	Low Density Parity Check Code
LFM	Linear-Frequency Modulation
LLR	Log-Likelihood Ratio
LLRV	Log-Likelihood Ratio Vector
LMMSE	Linear Minimum Mean-Square Error
LPF	Low Bandpass Filtering
LPM	Linear-Period Modulation
LS	Least Squares
MAC	Medium-Access Control
MACE10	Mobile Acoustic Communication Experiment in 2010
MAP	Maximum *A Posteriori* Probability
MCMC	Markov Chain Monte Carlo
MIMO	Multi-Input Multi-Output
ML	Maximum Likelihood
MP	Matching Pursuit
MSE	Mean Square Error
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
MUD	Multiuser Detection
MUI	Multiuser Interference
NC	Network Coding
NCM	Nonbinary Coded Modulation
NLNC	Network-Layer Network Coding
OFDM	Orthogonal Frequency-Division Multiplexing
OMP	Orthogonal Matching Pursuit
PAM	Pulse Amplitude Modulation
PAPR	Peak-To-Average-Power Ratio
PDA	Probabilistic Data Association
PER	Packet Error Rate
PLNC	Physical-Layer Network Coding
PSNR	Pilot Signal-To-Noise Ratio
QAM	Quadrature Amplitude Modulation
QC	Quasi-Cyclic

QMF	Quantize, Map and Forward
QPSK	Quadrature Phase Shift Keying
RIP	Restricted Isometry Property
RMSE	Root Mean-Squared Error
S2C	Sweep-Spread Carrier
SBL	Short Baseline
SDA	Sphere Decoding Algorithm
SIMO	Single-Input Multi-Output
SINR	Signal-to-Interference-and-Noise Ratio
SIR	Signal-to-Interference Ratio
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
SOFAR	Sound Fixing and Ranging
SONAR	Sound Navigation and Ranging
SPA	Sum Product Algorithm
SPACE08	Surface Processes and Acoustic Communication Experiment in 2008
SPRT	Sequential Probability Ratio Test
SUD	Single-User Detection
TCM	Trellis Coded Modulation
TDOA	Time Difference of Arrival
TVR	Transmitter Voltage Response
USBL	Ultra-Short Baseline
UUV	Unmanned Underwater Vehicle
UWA	Underwater Acoustic
VA	Viterbi Algorithm
ZF	Zero Forcing
ZP	Zero Padding

Notation

Scalars

K	Number of subcarriers in one OFDM symbol
B	Frequency bandwidth of one OFDM symbol
Δf	Subcarrier spacing in one OFDM symbol, $:= B/K$
T	Time-duration of one OFDM symbol, $:= 1/\Delta f$
T_{g}	Time-duration of guard interval for one OFDM symbol
T_{bl}	Time-duration of one OFDM block, $:= T + T_{\mathrm{g}}$
f_{c}	Center frequency of communication system
f_k	Frequency of the kth subcarrier, $:= f_{\mathrm{c}} + k/T$
$\mathcal{S}_{\mathrm{N}}$	The set of null subcarriers in one OFDM symbol
$\mathcal{S}_{\mathrm{P}}$	The set of pilot subcarriers in one OFDM symbol
$\mathcal{S}_{\mathrm{D}}$	The set of data subcarriers in one OFDM symbol
$\mathcal{S}_{\mathrm{A}}$	The set of active subcarriers in one OFDM symbol $:= \mathcal{S}_{\mathrm{P}} \bigcup \mathcal{S}_{\mathrm{D}}$
$h(t;\tau)$	Time-varying channel impulse response
$A_p(t)$	Time-varying amplitude of the pth path
A_p	Time-invariant amplitude of the pth path
$\tau_p(t)$	Time-varying delay of the pth path
τ_p	Initial delay of the pth path
a_p	Doppler rate of the pth path
N_{pa}	Number of paths in the channel
a	The main Doppler scaling factor in the UWA channel
ϵ	The residual Doppler shift after removing the main Doppler effect
ξ_p	The equivalent amplitude of the pth path in the baseband
$\overline{\tau}_p$	The equivalent scaled delay of the pth path in the baseband
b_p	The equivalent residual Doppler rate of the pth path in the baseband
D	ICI depth
$\mathcal{N}(\mu, \sigma^2)$	Real Gaussian distribution with mean μ and variance σ^2
$\mathcal{CN}(0, \sigma^2)$	Circularly symmetric complex Gaussian distribution with zero mean and variance σ^2
$\tilde{x}(t)$	The waveform in passband
$x(t)$	The waveform in baseband; Conversion between $\tilde{x}(t)$ and $x(t)$:

$$\tilde{x}(t) = 2\Re\{x(t)e^{j2\pi f_c t}\}$$
$$x(t) = \text{LPF}[\tilde{x}(t)e^{-j2\pi f_c t}]$$

Vectors and Matrices

$\mathbf{z}$	Measurement vector formed by frequency samples at all the OFDM subcarriers
$\mathbf{s}$	Transmitted symbol vector formed by symbols at all the OFDM subcarriers
$\mathbf{w}$	Ambient noise vector formed by the ambient noise at all the OFDM subcarriers
$\boldsymbol{\eta}$	Equivalent noise vector formed by the equivalent noise at all the OFDM subcarriers
$\mathbf{H}$	Channel mixing matrix
$\mathcal{CN}(0, \boldsymbol{\Sigma})$	Circularly symmetric complex Gaussian random vector with zero mean and covariance matrix $\boldsymbol{\Sigma}$

Operations

$\propto$	Equality of functions up to a scaling factor
$\lvert S \rvert$	Cardinality of set S
$[\mathbf{a}]_m$	The mth entry of vector $\mathbf{a}$
$[\mathbf{A}]_{m,k}$	The (m, k)th entry of matrix $\mathbf{A}$
$\{\mathbf{a}\}_{\ell=i}^{j}$	A set formed by elements $\{[\mathbf{a}]_i, \quad [\mathbf{a}]_{i+1}, \cdots, [\mathbf{a}]_j\}$
$\hat{a}$	The estimate of scale a
$\hat{\mathbf{a}}$	The estimate of vector $\mathbf{a}$
$\hat{\mathbf{A}}$	The estimate of matrix $\mathbf{A}$
$\mathbf{A}^{\mathrm{T}}$	The transpose of matrix $\mathbf{A}$
$\mathbf{A}^{\mathrm{H}}$	The complex conjugate transpose of matrix $\mathbf{A}$
$\mathbf{A}^{\dagger}$	The pseudo-inverse of matrix $\mathbf{A}$
$\mathrm{tr}(\mathbf{A})$	Trace of matrix $\mathbf{A}$
$\Pr\{\mathrm{A}\}$	Probability of an event A
$\mathbb{E}(X)$	Expectation of random variable X
$\mathbb{E}(\mathbf{x})$	Expectation of random vector $\mathbf{x}$
$\mathrm{Cov}(X, Y)$	Covariance of two random variables
$\mathrm{Cov}(\mathbf{x}, \mathbf{y})$	Covariance matrix of two random vectors
$\Re\{x\}$	Real part of a complex number x
$\Im\{x\}$	Imaginary part of a complex number x

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