

Principles of Cognitive Radio

Widely regarded as one of the most promising emerging technologies for driving the future development of wireless communications, cognitive radio has the potential to mitigate the problem of increasing radio spectrum scarcity through dynamic spectrum allocation.

Drawing on fundamental elements of information theory, network theory, propagation, optimization, and signal processing, a team of leading experts present a systematic treatment of the core physical and networking principles of cognitive radio, and explore key design considerations for the development of new cognitive radio systems.

Containing all the underlying principles you need to develop practical applications in cognitive radio, this book is an essential reference for students, researchers, and practitioners alike in the field of wireless communications and signal processing.

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“Solidly global perspective on the foundations and advanced topics of one of the most important developments in radio systems engineering in the past several decades – this book is a landmark publication, a compelling page-turner in presentation and a valuable reference resource for practicing radio engineers.”

Dr. Joseph Mitola III, Mitola’s STATISfaction

“This is the first book to cover the topic of cognitive radio from a fundamental viewpoint. It provides new insights on propagation, spectrum sensing, system optimization and networking that will be invaluable to theoretical researchers as well as practitioners in the field.”

Venugopal V. Veeravalli, University of Illinois at Urbana-Champaign

“Much has been written on the ever-expanding subject of cognitive radio. The new book entitled “Principles of Cognitive Radio”, written by well-respected authorities, fills a gap by presenting detailed discussions of different aspects of this fascinating subject. I recommend the book for use by researchers who are already working in cognitive radio or planning to move into it.”

Simon Haykin, McMaster University, Canada

“Principles of Cognitive Radio” is a comprehensive treatment of many of the fundamental issues that will impact cognitive wireless communications networks of the future. The authors have done an excellent job bringing together many modern concepts that are at the forefront of wireless, while reviewing the fundamentals along the way. As a result, the authors have created an excellent reference text, bringing a wide range of problems, contributions, and viewpoints together in a single, well-written book.”

*Theodore S. Rappaport, Polytechnic Institute of New York University and Director,
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To our families

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Preface

The radio spectrum is one of the most important resources for communications. Traditionally, spectrum governance throughout the world has tended towards exclusivity of its use in large geographic areas, allocating frequency bands for specific applications and assigning licenses to specific users or service providers. This policy has generated a shortage of frequencies available for emerging wireless products and services, as most frequencies are now assigned. Moreover, exclusivity creates underutilization of the spectrum, as very rarely can all licensees make full use of the frequencies assigned to them. These facts have motivated the search for technologies able to alleviate the artificial scarcity of spectrum by adapting to changing environmental and network-usage conditions.

What is perhaps the most natural among these technologies involves *opportunistic* use of the spectrum, whereby *secondary* (unlicensed) users are able to occupy the portions of the spectrum left temporarily free by the licensed *primary* users. The stringent requirement here is that secondary users should not interfere with the primary users, which this paradigm of operation (later called *interweaving*) achieves using the simplest form of orthogonalization, one that only requires knowledge of the state of a frequency band, i.e., whether it is free or occupied. The fact that the spectrum can be shared by primary and secondary users, with the latter exploiting their cognition of the environment in which transmission is taking place, has led to the development of the concept of *Cognitive Radio* (CR), whose idea was first introduced in [1] in 1999. Further paradigms, potentially more efficient than interweaving, have subsequently emerged. In the *underlay* paradigm, the secondary transmitter overlaps in frequency with the primary user, after making sure that the interference level it causes is below a given threshold. The *overlay* paradigm assumes that the secondary user has knowledge of the primary user's transmission scheme and of the channel, and uses this knowledge by choosing a transmission scheme that causes an irrelevant amount of interference.

In its multiple aspects, CR is now widely regarded as one of the most promising technologies for future wireless communications, a technology that may potentially mitigate, through dynamic spectrum access, the radio spectrum scarcity problem. The US Federal Communications Commission has approved the use of mobile devices in unused television bands, and there is considerable support worldwide for this new concept. Wide interest in the field has also been displayed in academic research. Since CR theory is still in its early stage, there is a need for a book describing the principles on which CR is based, and laying out in a unified way the background needed for further

developments and innovative applications. This background blends propagation theory, information theory, detection theory, optimization theory, networking, and signal processing. Given the importance of the discipline, and the number of unique features that characterize it, this book, which covers the fundamental aspects of CR and especially those that are the most promising for commercial implementation, should be of considerable interest to researchers and practitioners in this field.

This book is organized into five chapters, each meant to be self-contained (with the possible exception of Chapter 5, which may need knowledge of material in Chapter 4 if the reader is not conversant with the basics of detection theory). Chapter 1 introduces the concepts of CR, illustrates the present and future of spectrum management policies, and examines network design and standardization activity. Chapter 2 is devoted to the information-theoretic aspects of CR. Specifically, it develops the fundamental capacity limits, guidelines for the spectral efficiency possible in CR using each of its three paradigms, as well as practical design ideas to optimize performance. These fundamental limits are based on the amount of side information that can be gathered about the radio environment and can be used to improve spectrum utilization as well as the complexity of the CR technique employed. Chapter 3 describes the propagation channels that are typical of CR environments, and presents models for path loss, Doppler spectrum, delay spread, and other relevant features. These models are useful to both designers and analysts, who need to characterize the spectral, temporal, and spatial variations of the channel responses in CR networks. Chapter 4 describes techniques for spectrum sensing, to be used in interweaving and underlay. Interweaving involves the classification and the performance analysis of a number of decision rules intended to identify spectral regions that are empty and hence can be used by secondary users, while underlay is treated by introducing the concept of interference temperature. Finally, Chapter 5 contains the discussion of a number of advanced topics related to spectrum exploration and exploitation. These include techniques, such as distributed, sequential and quickest detection, that are important in optimizing spectrum sensing and identifying available spectral opportunities. This chapter further explores high-level methodologies, including dynamic programming, bandit problems, reinforcement learning, and game theory, in the context of their applications to sensing and access policy design for CR systems. We hasten to observe here that space limitations prevent us from covering the whole range of CR-related topics. In particular, this book does not cover many of the networking aspects of CR, protocols, and standardization efforts.

Our presentation of the subject aspires to combine the features of a textbook and a guide through the research literature. Thus, the book is aimed at graduate students and researchers, as well as at practitioners in industry. Having an emphasis on principles, it can be used as a textbook in a beginning-graduate course entirely devoted to CR, or as a complementary book in courses devoted to wireless communications. It was written assuming no special prerequisite knowledge for reading it, beyond the usual contents of basic communication, information theory, and signal processing courses given in standard electrical engineering curricula. These basics are extended here to the theoretical aspects of CR that are specific to this new technology.

While we know that no book is so poorly written that it cannot be useful in some part, we are also aware that no book is so perfect that nothing wrong can be found in it. Thus, we would be grateful to readers who inform us of any mistakes or inaccuracies that they may find herein.

References

- [1] J. Mitola III, *Cognitive Radio: Model-Based Competence for Software Radio*, Licentiate Thesis, The Royal Institute of Technology. Stockholm, Sweden, Aug. 1999.

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Notation

General notation and symbols

$A(\cdot)$	Autocorrelation function
\mathbf{A}^T	Transpose of the matrix \mathbf{A}
\mathbf{A}^H	Hermitian of the matrix \mathbf{A}
\mathcal{A}^c	Complement of the set \mathcal{A}
B_c	Coherence bandwidth
$c(\cdot)$	Cost function
C	Channel capacity
C_{erg}	Ergodic channel capacity
C_{out}	Outage channel capacity
\mathbf{C}	Channel capacity region
\mathbb{C}	Set of complex numbers
$\mathbb{E}[\cdot]$	Expectation operator
$D(\cdot)$	Doppler power spectrum
f	Frequency
f_c	Center frequency of the signal band
$F(\cdot)$	Frequency correlation function
$F_X(\cdot)$	Cumulative distribution function of the RV X
$g_d(\cdot), g_e(\cdot)$	Decoding, encoding function.
G	Power gain
G_r, G_t	Receive, transmit antenna gains, in dB
γ	Signal-to-noise ratio, path loss exponent
h	Complex channel gain
$h(t)$	Channel impulse response
$H(f)$	Complex frequency response of a channel or filter
H	Mean-square value of $ h $
\mathbf{H}	Channel gain matrix
\mathcal{H}_0	Null hypothesis
\mathcal{H}_1	Alternative hypothesis
η	Efficiency
\mathbf{I}	Identity matrix
\mathbf{I}_k	$k \times k$ identity matrix
$I(X; Y)$	Mutual information between X and Y

K	Ricean K -factor
λ	RF wavelength
Λ	Likelihood ratio
$\ln x$	Natural logarithm of x
$\log_x y$	Logarithm, base x , of y
M_r, M_t	Number of receive, transmit antennas
ν	Doppler frequency
n	Discrete time index (in the subscript)
n_B	Number of frequency bands
N	Noise power
N_0	Power spectral density of white noise
$p_X(\cdot)$	Probability density function of the RV X
$p(y x)$	Conditional probability of y given x
$\mathbb{P}[A]$	Probability of event A
P_D	Probability of correct detection
P_e	Probability of error
P_{FA}	Probability of false alarm
P_{MD}	Probability of missed detection
P_{on}, P_{off}	Probability that a switch is on or off
P_{out}	Probability of outage
\mathcal{P}	Power
\mathcal{P}_r	Receive power
\mathcal{P}_t	Transmit power
$\mathcal{P}(\cdot)$	Power delay profile
\mathcal{P}_{peak}	Peak power constraint
$Q(\cdot)$	Gaussian tail function
$Q(\cdot, \cdot)$	Normalized incomplete Gamma function
$Q_N(\cdot, \cdot)$	Generalized Marcum Q -function
$\mathcal{Q}(\cdot)$	Action-value function
$\mathcal{Q}^*(\cdot)$	The optimal action-value function
ρ	Correlation
R	Transmission rate
\mathbb{R}	Set of real numbers
$\Re[\cdot]$	Real part
$\text{rank}(\mathbf{H})$	Rank of matrix \mathbf{H}
s	Channel state
\mathcal{S}_c	Set of all channel states
\mathcal{S}_{PR}	Set of primary receivers
\mathcal{S}_{ST}	Set of secondary transmitters
$(\mathcal{S}, \mathcal{S}^c)$	A network cut between nodes in \mathcal{S} and nodes in \mathcal{S}^c
S	Shadow fading, in dB
σ	Standard deviation of shadow fading
σ_X^2	Variance of random variable X

snr	Signal-to-noise ratio
τ	Multipath delay
τ_{rms}	rms multipath delay spread
t	Continuous time index
$u(t)$	Unit-step function
u_i	Local sensor mapping (e.g., a binary decision)
$\mathcal{V}(\cdot)$	Value function
$\mathcal{V}^*(\cdot)$	The optimal value function
V	Time-sharing random variable
$w(t)$	Continuous-time white noise process
w_n	Discrete-time white noise process
W	Bandwidth
X_c	Correlation distance of shadow fading
$\frac{\partial}{\partial x}$	Partial derivative with respect to x
\hat{x}	Estimate of x
\mathbf{x}	A vector
$\ \mathbf{x}\ $	Euclidean norm of the vector \mathbf{x}
x^n	A vector with elements (x_1, \dots, x_n)
$x(t)$	Continuous-time transmitted signal
x_n	Discrete-time transmitted signal at time n
$ \mathcal{X} $	Cardinality of the set \mathcal{X}
$X \in \mathcal{X}$	X is an element of the set \mathcal{X}
$X \sim \mathcal{N}(\mu, \sigma^2)$	X is a real, Gaussian RV with mean μ and variance σ^2
$X \sim \mathcal{N}_c(\mu, \sigma^2)$	X is a circularly symmetric Gaussian RV with mean μ and variance σ^2
$y(t)$	Continuous-time received signal
y_n	Discrete-time received signal at time n
$z(t)$	Continuous-time noise process
z_n	Discrete-time noise process

Acronyms and abbreviations

3G	Third-generation cellular systems
AAA	Authentication, authorization, and accounting
ACF	Autocorrelation function
ADC	Analog to digital converter
ALOHA	The ALOHA random access protocol
AoA	Angle of arrival
AOD	Angle of departure
APS	Angular power spectrum
ARQ	Automatic repeat on request
ART	Above roof top

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AS	Angular spread
AWGN	Additive white Gaussian noise
BE	Bandwidth exchange
BEP	Bit-error probability
BP	Belief propagation
BS	Base station
CAF	Cyclic autocorrelation function
CAGR	Compound annual growth rate
CDF	Cumulative distribution function
CDMA	Code division multiple access
CEPT	European Conference of Postal and Telecommunications Administrations
CFAR	Constant false-alarm rate
CR	Cognitive radio
CSD	Cyclic spectral density
CSI	Channel-state information
CSMA	Carrier sense multiple access
CSMA/CA	Carrier sense multiple access with collision avoidance
CUSUM	Cumulative sum
DAB	Digital Audio Broadcasting
DAI	Dynamic allocation index
DDDPS	Double-directional delay power spectrum
DDIR	Double-directional impulse response
DFT	Discrete Fourier transform
DHCP	Dynamic host configuration protocol
DMDT	Diversity–multiplexing–delay tradeoff
DMT	Diversity–multiplexing tradeoff
DNS	Domain name service
DOA	Direction of arrival
DOD	Direction of departure
DPC	Dirty paper coding
DS	Delay spread
DSA	Dynamic spectrum access
DSL	Digital subscriber line
D-SPRT	Decentralized SPRT
DVB	Digital video broadcasting
ECC	European Communications Committee
EGC	Equal-gain combining
ETSI	European Telecommunications Standards Institute
EWSPT	Enhanced weighted SPRT
EWSZOT	Enhanced weighted sequential zero/one test
FC	Fusion center
FCC	Federal Communications Commission
FCF	Frequency correlation function

FFT	Fast Fourier transform
FM	Frequency modulation
FPGA	Field programmable gate array
FSPL	Free-space power loss
FTTH	Fiber to the home
GCP	Global control plane
GLLR	Generalized log-likelihood ratio
GLR	Generalized likelihood ratio
GPS	Global positioning system
GRF	Gain reduction factor
HMM	Hidden Markov model
ICI	Intercarrier interference
IDFT	Inverse discrete Fourier transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse fast Fourier transform
IMT-Advanced	International Mobile Telecommunications – Advanced
IWFA	Iterative waterfilling algorithm
iid	Independent and identically distributed
IP	Internet protocol
ISI	Inter-symbol interference
ISM	Industrial, scientific and medical
ITU	International Telecommunications Union
LAN	Local-area network
LFD	Least favorable distribution
LOS	Line-of-sight
LDPC	Low-density parity-check
LLR	Log-likelihood ratio
LTE	Long-term evolution
MAC	Medium access control
MAP	Maximum a posteriori
MDP	Markov decision process
MEMS	Micro-electronic mechanical systems
MIMO	Multiple-input, multiple-output
MMSE	Minimum mean-square error
MP	Marginal productivity
MPC	Multipath component
MRC	Maximal-ratio combining
MS	Mobile station
MSE	Mean-square error
MSPRT	M -ary SPRT
NC-OFDM	Noncontiguous orthogonal frequency division multiplexing
NIS	Network interference server
NLOS	Non-line-of-sight
NTIA	National Telecommunications and Information Administration

OFDM	Orthogonal frequency-division multiplexing
P2P	Peer-to-peer
PAPR	Peak-to-average power ratio
PC	Personal computer
pdf	Probability density function
PDP	Power–delay profile
PHY	Physical layer
pmf	Probability mass function
POMDP	Partially observable Markov decision process
PSD	Power spectral density
PSK	Phase-shift keying
QoS	Quality of service
RF	Radio frequency
RMS	Root-mean-square
ROC	Receiver operating characteristics
RSS	Received signal strength
RST	Repeated significance test
RUCB	Restless UCB
RV	Random variable
RX	Receiver
SAP	Sensing assignment problem
SCM	Spatial channel model
SD	Sequential detection
SDR	Software-defined radio
SIC	Successive interference cancellation
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
SoC	System on a chip
SPRT	Sequential probability ratio test
SR	Shiryaev–Roberts
SRP	Shiryaev–Roberts–Pollak
SSCT	Sequential shifted chi-square test
SSPRT	Shiryaev SPRT
TCP	Transmission control protocol
TDFS	Time-division fair sharing
TDMA	Time-division multiple access
TV	Television
TVWS	Television white space
TX	Transmitter
UCB	Upper confidence bound
UHF	Ultrahigh frequency
UWB	Ultra-wideband
VI	Variational inequality
V2V	Vehicle-to-vehicle

WiFi	Wireless fidelity, refers to devices using IEEE 802.11 family of standards
WiMAX	Worldwide interoperability for microwave access
WS	White space
WSN	Wireless sensor network
WSPRT	Weighted SPRT
WWAN	Wireless wide area network