

## White Space Communication Technologies

Increase the efficient use of time-varying available spectrum with this unique book, the first to describe RF hardware design for white space applications, including both analog and digital approaches. Emerging technologies are discussed and signal processing issues are addressed, providing the background knowledge and practical tools needed to develop future radio technologies.

Real-world examples are included, together with global spectrum regulations and policies, for a practical approach to developing technologies for worldwide applications. Cross analog and digital design guidelines are provided to cut design time and cost.

This holistic, system level view of transceiver design for white space technologies is ideal for practicing engineers and students and researchers in academia.

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# Preface

White space technologies is an area of great interest in the technology, information, and communication field, due mainly to the possibility to have cooperating radios that will optimize the transmission parameters to achieve the best possible performance. This area achieved even greater importance due to the possibility to use frequency bands that are under-utilized, or are used sparsely – one of the cases being the TV band that was empty after the analog-to-digital TV switch over.

White space radios should be agile and adapt to the radio interface with a clear view and optimized operation; that is why special care should be taken with these types of radio and a special design procedure should be followed and discussed. It is exactly in this area that this book fits, by discussing technological implementation details and processes that are fundamental for building cognitive radios that will be the basis of white space devices.

The book is divided into three parts, each one with three chapters. The first part is focused on the general problems we face in white space technology and signal processing. The second part will focus on adaptable receivers for white space devices, and the final part will be focused on adaptable transceivers.

The first chapter of the book “White space technology, the background” will start the discussion of these radios and give some technological views. In this chapter, white space technology will be discussed and the operational details of cognitive radio architectures, how these new radio systems will be able to adapt themselves to the environment, and how they will be able to manage conveniently the data transmission speed with optimum spectrum occupancy, but also energy awareness, will be discussed. A brief explanation of white space technologies, addressing the main hardware limitations of cognitive radio architectures, will be presented. Special attention will also be given to multi-carrier and noncoherent OFDM approaches, and the impact these new kinds of signal could have on front-ends.

The second chapter “Transceiver challenges for white space radio” provides an overview of transceiver challenges and solutions specific to cognitive and software-defined radio. Interference scenarios for white space radio are developed as a model for receiver linearity requirements. Transmitter linearity requirements for white space radio transceivers are reviewed along with the implications for transmitter power efficiency. State-of-the-art architectures and circuit solutions for configurable high dynamic range CMOS integrated transceivers are presented. Specific approaches to high dynamic range

receivers that are tolerant of large amplitude off-channel interfering signals are also reviewed.

The third chapter “Front-ends for software-defined radio” will discuss front-ends, inspired by the human cochlea, that could solve dynamic range and bandwidth problems by using a hybrid filter bank to convert the RF signal to the digital domain. The main advantages of this solution will be presented and will demonstrate how digital signal processing machinery could help. A review of spectrum sensing techniques and dynamic spectrum aggregation will be performed, and the operation of the hybrid filter bank will be discussed and how it can have a key role to make these operations effective.

The fourth chapter “Reconfigurable RF front-ends for cognitive and software-defined radio” presents and discusses RF-front-end components designed for cognitive and software-defined radio systems, with emphasis on receiver solutions for high dynamic range and re-configurability. An overview of classical and emerging RF analog front-end receiver architectures such as heterodyne and zero-IF is presented in terms of related advantages and drawbacks per system requirements. The performances of main RF front-end receiver components such as filters, and active and passive tunable mixers, are studied and compared. Different design techniques and technological processes used for the development of tuning elements are also presented with performance comparisons in terms of frequency tuning range, loss, supply voltage, and linearity. The design methodology and implementation of frequency-agile multi-port interferometer techniques made of tunable bandpass filters, diplexers and couplers based on available semiconductor and ferroelectric materials are examined as a potential and cost-effective solution for a reconfigurable direct-conversion receiver platform. Performance comparisons of different tunable receiver architectures are presented and analyzed in this chapter; one structure relying on a tunable bandpass filter, and the other system based on a semiconductor varactor-based tunable passive mixer, with the latter showing better sensitivity and dynamic range. In summary, an integrated circuit level of electronically tunable mixers based on interferometer techniques presents great potential and a cost-effective solution for cognitive and software-defined radio platforms, with particular interest for advanced multi-mode, multi-band wireless transceivers with carrier aggregation capability.

Next, the fifth chapter will discuss filtering strategies, “Filtering stages for white space cognitive/software-defined radio receivers”, and presents a description of the necessities of filtering stages for receiver modules in the white space communications scenario. Specifically, two different receiver configurations are studied, with focus on the filtering blocks carrying out the signal selection. The first one is a mixed-domain receiver structure simultaneously exploiting both analog and digital signal processing concepts under the “hybrid filter bank” philosophy. The key principle for the proper operation of this receiver solution is the exhaustive channelization of the incoming desired signal into narrower signal subbands. This must be performed through sophisticated contiguous-band high-order multiplexers at both the RF and IF levels. The second one is a direct-sampling receiver solution for multi-channel communications working at subNyquist rates. The core part of this class of receiver is the multi-band filter that acquires all the signal subbands at the same time, which are subsequently

sampled at subNyquist rates. This type of multi-band filter should be designed by means of signal-interference techniques, since classic coupled-resonator networks can exhibit serious deficiencies for this application. For all the filtering devices reported in this chapter, main issues about their theoretical design are detailed. Furthermore, real proof-of-concept prototypes are developed and characterized.

The sixth chapter “Subsampling multi-standard receiver design for cognitive radio systems” will discuss the requirements for a cognitive radio system and how multi-standard requirements come into the picture, conventional receiver architectures and their problems, how a subsampling receiver solves these problems, and gives a description of a subsampling receiver, including its advantages and disadvantages. In this chapter, a close view is given of subsampling receivers and how their impact on white space technology will be fundamental; furthermore, there will also be a discussion on why optimization is required for basic subsampling receiver architecture for the multi-standard case, as well as on the typical requirements that force optimization.

The seventh chapter will be focused on “White spaces exploration using FPGA-based all-digital transmitters” and will discuss the design challenges inherent in flexible RF transmitters for exploring the TV white spaces and the recent advances in FPGA-based multi-mode and multi-channel all-digital transmitters. The chapter starts with an introduction to the design challenges of RF transmitters targeting white space systems followed by a discussion on how all-digital transmitters implemented on FPGA technology will address some important requirements, such as flexibility, integration, and power efficiency. The second part of the chapter is devoted to the presentation and discussion of the operation principles, architectures, and design of all-digital transmitters based on different approaches. The recent techniques for improving important figures of merit, such as bandwidth, in-band and out-of-band noise, filtering requirements, coding and power efficiency are also described and compared. The chapter ends with a discussion on promising future research directions.

The eighth chapter will discuss “Interference active cancelation techniques for agile transceivers” starting with a review of the basic and advanced transceiver architectures suitable for cognitive radios. It first introduces the figures of merit of the transceivers along with the main effects which degrade overall performance. Receiver desensitization due to the combined effects of both interference and the transmitter leakage signal at the receivers is explained by system-level analysis. This impairment makes the design of transceivers for white spaces more challenging than for conventional application and can be solved by either sharp notch filters or dynamic signal cancelation at the receiver input. The latter is covered in detail along with an explanation of the related algorithm. The architectures under consideration largely share the digital IF technique as an effective way to ensure high flexibility with respect to modulation modes and spectra.

Finally the book will end with a thorough analysis of “highly efficient transmitter architectures” and there will be a discussion on the several highly efficient transmitter architectures that have been proposed, and even revived, aimed at enhancing typical Class AB PA efficiency figures in Cartesian transmitters. The chapter addresses state-of-the-art, highly efficient transmitter architectures that are potential candidates to be used in white space scenarios. Hence, architectures such as linear amplification with

nonlinear components (LINC), Doherty PAs, polar transmitters with pulsed/delta-sigma modulation, envelope elimination and restoration (EER), and envelope tracking (ET) will be examined in the chapter.

The work to write and finish a book is not exclusively that of the authors, but includes the help and collaboration of many people who somehow cross our paths during this process. So we would like to express our gratitude to many people who directly, or indirectly, helped us to carry on this task.

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# Abbreviations

|      |   |
|------|---|
| ADC  | analog-to-digital converter   |
| AFB  | analogue filter bank  |
| AGC  | analog gain control   |
| AMI  | advanced metering infrastructure                                    |
| ASIC | application-specific integrated circuit                             |
| ASSP | application-specific standard product                               |
| BER  | bit-error rate  |
| CEPT | European Conference of Postal and Telecommunication Administrations |
| CIFB | cascade of integrator with distributed feedback                     |
| CMOS | complementary metal oxide semiconductor                             |
| CMRS | commercial radio service  |
| CR   | cognitive radio   |
| CSDR | cognitive and software defined radio                                |
| DAC  | digital-to-analog converter   |
| DCR  | direct conversion receiver  |
| DFB  | digital filter bank   |
| DFT  | discrete Fourier transform  |
| DPD  | digital pre-distortion  |
| DSP  | digital signal processor (processing)                               |
| DTT  | digital terrestrial TV  |
| DTV  | digital television  |
| DUC  | digital up-conversion   |
| EC   | European Commission   |
| ECA  | European Common Allocation  |
| ECC  | Electronic Communications Committee                                 |
| EIRP | equivalent isotropic radiated power                                 |
| ENOB | effective number of bits  |
| ERP  | effective radiated power  |
| EVM  | error vector magnitude  |
| FCC  | Federal Communications Commission                                   |
| FDD  | frequency division duplex   |
| FET  | field effect transistor   |
| FIR  | finite impulse response   |

|       |   |
|-------|---|
| FPGA  | field programmable gate array               |
| GPP   | general-proposed processors                 |
| HAAT  | height above average terrain                |
| HAGL  | height above ground level                   |
| HDTV  | high definition TV                          |
| HFB   | hybrid filter banks                         |
| IC    | integrated circuit                          |
| IF    | intermediate frequency                      |
| IFVGA | IF variable gain amplifier                  |
| IRR   | image rejection ratio                       |
| ISM   | industrial, scientific, and medical         |
| LCM   | low common multiple                         |
| LCP   | liquid crystal polymer                      |
| LNA   | low noise amplifier                         |
| LO    | local oscillator                            |
| LP    | low pass                                    |
| LPF   | low-pass filter                             |
| LSB   | lower sideband                              |
| LTCC  | low-temperature co-fired ceramic            |
| LTE   | long-term evolution                         |
| MER   | modulation error ratio                      |
| MVPD  | multi-channel video programming distributor |
| NF    | noise figure                                |
| NTF   | noise transfer function                     |
| OFDM  | orthogonal frequency-division multiplexing  |
| OMUX  | output multiplexer                          |
| OSR   | oversampling ratio                          |
| PA    | power amplifier                             |
| PAPR  | peak-to-average power ratio                 |
| PLMRS | private land mobile service                 |
| PMSE  | programme making and special events         |
| POCS  | projections on to convex sets               |
| PQN   | pseudo quantization noise                   |
| PU    | primary user                                |
| PWM   | pulse width modulation                      |
| QAM   | quadrature amplitude modulation             |
| QBPS  | quadrature bandpass sampling                |
| RAN   | radio access network                        |
| RF    | radio frequency                             |
| RFIC  | radio frequency integrated circuits         |
| RFID  | radio frequency identification              |
| RFVGA | RF variable gain power amplifier            |
| RSC   | Radio Spectrum Committee                    |
| RSPG  | Radio Spectrum Policy Group                 |

|       |   |
|-------|---|
| SASP  | sampled analog signal processor                 |
| SAW   | surface acoustic wave                           |
| SDR   | software-defined radio                          |
| SFB   | synthesis filter bank                           |
| SFDR  | spurious-free dynamic range                     |
| SIW   | surface integrated waveguide                    |
| SMPA  | switched-mode power amplifier                   |
| SNR   | signal-to-noise ratio                           |
| SU    | secondary user                                  |
| SQNR  | signal-to-quantization noise ratio              |
| SSB   | single sideband                                 |
| STF   | signal transfer function                        |
| TDD   | time-division duplex                            |
| TVBD  | TV band devices                                 |
| TVWS  | TV white spaces                                 |
| USB   | upper sideband                                  |
| VCO   | voltage-controlled oscillator                   |
| VGA   | variable gain amplifier                         |
| VNA   | vector network analyzer                         |
| VSA   | vector spectrum analyzer                        |
| WCDMA | wideband code division multiple access          |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WSD   | white space device                              |