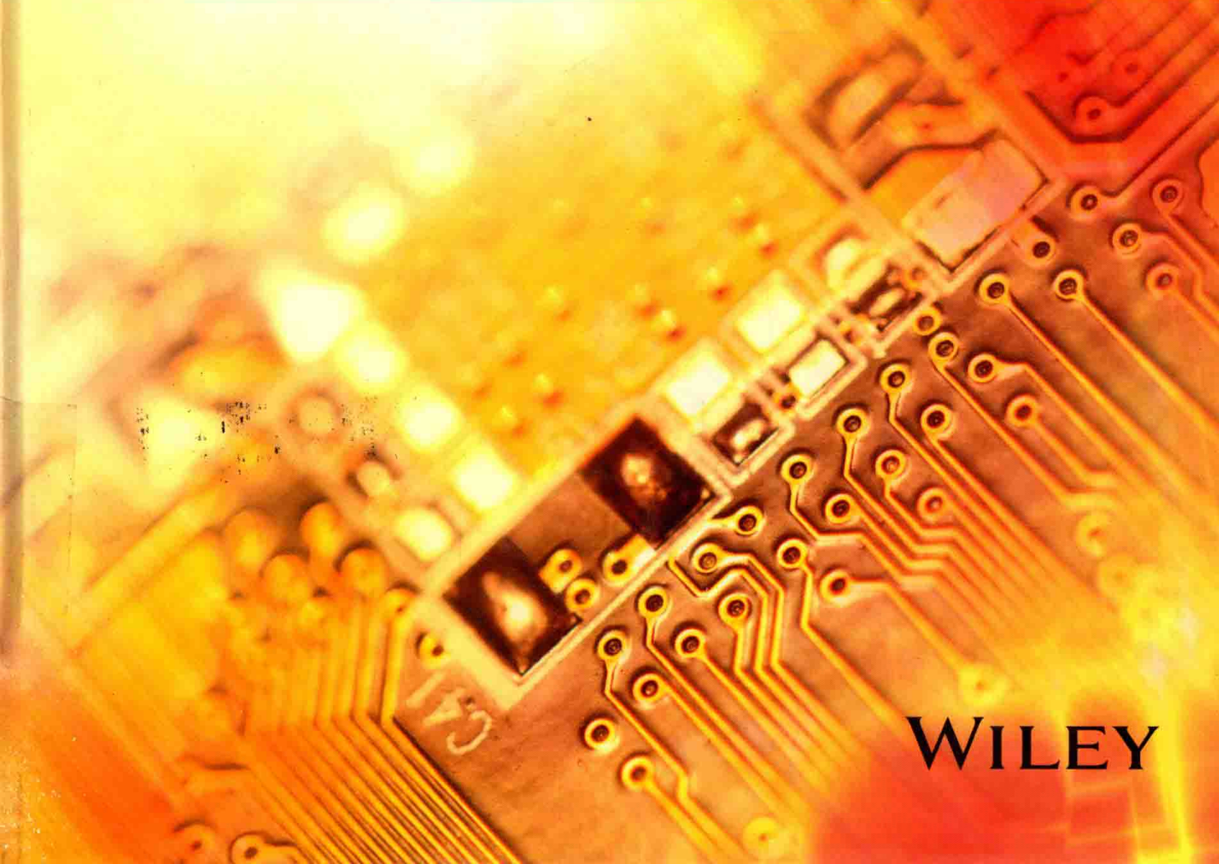
Pierre Baudin

Wireless Transceiver Architecture

Bridging RF and Digital Communications



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WIRELESS TRANSCEIVER ARCHITECTURE

To my children, Hugo and Chloé, and in memory of my parents

Preface

The origins of this book lie in the frequent questions that I have been asked by colleagues in the different companies I have worked for about how to proceed in the dimensioning and optimization of a transceiver line-up. The recurrence of those questions, along with the problem of identifying suitable reference sources, made me think there could be a gap in the literature. There is indeed an abundant literature on the physical implementation of wireless transceivers (e.g. the RF/analog CMOS design), or on digital communications theory itself (e.g. the signal processing required), but little on how to proceed for dimensioning and optimizing a transceiver line-up.

Furthermore, the fact is that those questions were coming from two distinct categories of engineers. On the one hand, RF/analog designers are curious to understand how the specifications of their blocks are derived. On the other hand, the digital signal processing engineers in charge of the baseband algorithms need to understand the mechanisms involved in the degradation of the wanted signal along the line-up for optimizing their processing. Obviously, it is the job of an RFIC architect to make the link between the two communities and to attempt to overcome the communication problems between those two groups. Roughly speaking, you have on the one hand the baseband engineers that process complex envelopes while benchmarking their algorithms using AWGN, and on the other hand the RF/analog designers that optimize their designs based on the use of CW tones for evaluating the degradation of a signal expected to be modulated. Based on my experience, even if the difficulty in the discussion can be related somehow to the different nature of the technical issues addressed by the two communities, it is also closely related to the different formalisms traditionally used in those two domains of knowledge.

I therefore wrote this book with two aims in mind. I first tried to detail the mindset required, at least based on my professional experience, to take care of the system design of a transceiver. Expressed like this, we understand that the purpose is not to be exhaustive about how to perform such dimensioning for all the architectures one can imagine. Rather the goal is to explain the spirit of it, and how to initiate such work in practice. Conversely, in order to be able to react correctly whatever the architecture under consideration, there is a need to understand as far as possible the constraints we have to take into account in order to dimension a transceiver. Practically speaking, this means understanding the system design of transceiver line-up in its various aspects. We can, for instance, mention the need to understand the purpose of a transceiver from the signal processing perspective. Indeed, from the transmitted or received signal point of view, the transceiver implements nothing more than signal processing functions, mainly analog signal processing, but signal processing when all is said and done. Alternatively, we can mention the need to understand the various limitations one can face in the implementation of this analog signal processing using electronic devices. Those limitations can indeed be encountered whatever the architecture implemented.

I then also tried to unify the formalisms used in the various domains of knowledge involved in the field of wireless transceivers. In practice, this means considering the digital communications formalism and the extensive use of the complex envelope concept for modeling modulated RF signals. As discussed above, the first goal was to make easier the link between RF and digital communications people who need to work together in order to optimize a line-up. This approach also happens to have many additional benefits. It allows us to correctly define RF concepts for modulated signals often introduced in a more intuitive way. It also allows us to perform straightforward analytical derivations in many situations of interest, as in nonlinearity for instance, while allowing explicit graphical representations in the complex plane. I am now fully convinced that this formalism is of much interest to RF problems and I would be pleased if this book can help to propagate its use.

As a result, this book consists of three parts. Part I focuses on the explanation of what is expected from a transceiver. This part is composed of three chapters dedicated to the three areas that drive those requirements: (a) the digital communications theory itself, which allows us to define the minimum set of signal processing functions to be embedded in a transceiver, as well as introducing key concepts such as complex envelopes; (b) the electromagnetism theory, as theoretical results in the field of propagation allow us to explain some architectural constraints for transceivers; (c) the practical organization of wireless networks, as it drives most of the performance required from transceivers in practice. By the end of Part I we should thus have an understanding of the functionalities required in a transceiver as well as their associated performance.

Part II is then dedicated to a review of the limitations we face in the physical implementation using electronic devices of the signal processing functions derived in Part I. Those limitations are sorted into three groups, leading to three chapters dedicated to: (a) the noise sources to be considered in a line-up; (b) the nonlinearity in RF/analog components; (c) what are classically labeled RF impairments.

Part III then turns to the transceiver architecture and system design itself. We can now focus on how to dimension a transceiver that fulfills the requirements derived in Part I while taking into account the implementation limitations reviewed in Part II. Practically speaking, this is done through three chapters. The first of these is dedicated to the illustration of a transceiver budget for a given architecture. This shows how a practical line-up budget can be done, i.e. how the constraints linked to the implementation limitations can be balanced between the various blocks of a given line-up in order to achieve the performance. The second chapter reviews different architectures of transceivers. In contrast to what is done in the previous chapter, we can see here how the fundamental limitations of a given line-up can be overcome by changing its architecture. The third chapter then examines some algorithms classically used for improving or optimizing the performance of transceiver line-ups.

At this stage, I need to highlight that, due to the organization of the book, only the reasoning used for the architecture and system design of transceivers is discussed in Part III. All the theoretical results, as well as the description of the elementary phenomena that are involved in this area, are detailed in Parts I and II. As a result, I recommend that the reader should not embark on Part III without sufficient understanding of the phenomena discussed in Parts I and II.

To conclude, I would like to thank all those people who helped in completing this project. First of all, I would like to thank my former colleagues at Renesas who participated in one way or another during this project, i.e. Alexis Bisiaux, Pascal Le Corre, Mikaël Guenais, Stéphane Paquelet, Arnaud Rigollé, Patrick Savelli, and in particular Larbi Azzoug and Anis Latiri. Then, I would like to warmly thank Marc Hélier, who taught me microwave engineering at Supélec some years ago, and who was kind enough to go through Chapter 2. Finally, I would like to thank Fabrice Belvèze, as it was all the good technical discussions we had during the old STMicroelectronics times that first convinced me that it was interesting to using the digital communications formalism for the system design of transceiver line-up. Things have changed since then, but the origins are there.

Rennes, January 2014

List of Abbreviations

ABB	Analog Baseband
ACPR	Adjacent Channel Power Ratio
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
ADC	Analog to Digital Converter
ADPLL	All Digital PLL
AFC	Automatic Frequency Correction
AGC	Automatic Gain Control
AM	Amplitude Modulation
AWGN	Additive White Gaussian Noise
BBIC	Baseband IC
BER	Bit Error Rate
BTS	Base Transceiver Station
CALLUM	Combined Analog Locked Loop Universal Modulator
CCP	Cross-Compression Point
CDMA	Code Division Multiple Access
CDE	Code Domain Error
CDF	Cumulative Distribution Function
CCDF	Complementary Cumulative Distribution Function
CDP	Code Domain Power
CF	Crest Factor
CMOS	Complementary Metal Oxide Semiconductor
CORDIC	COordinate Rotation DIgital Computer
CP	Compression Point
CW	Continuous Wave
DAC	Digital to Analog Converter
DC	Direct Current
DNL	Differential NonLinearity
DR	Dynamic Range
DSB	Double SideBand
DtyCy	Duty Cycle
EDGE	Enhanced Data Rates for GSM Evolution
EER	Envelope Elimination and Restoration
EMF	ElectroMotive Force

EMI	ElectroMagnetic Interference
ERR	Even Order Rejection Ratio
ET	Envelope Tracking
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FE	Front-End
FEM	Front-End Module
FIR	Finite Impulse Response
FM	Frequency Modulation
FS	Full Scale
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile communications
HPSK	Hybrid Phase Shift Keying
I/F	InterFace
IC	Integrated Circuit
ICP	Input Compression Point
ICCP	Input Cross-Compression Point
IF	Intermediate Frequency
IIP	Input Intercept Point
IMD	Intermodulation Distortion
INL	Integral NonLinearity
IP	Intercept Point
IPsat	Input Saturated Power
IRR	Image Rejection Ratio
ISI	InterSymbol Interference
ISR	Input Spurious Rejection
LINC	LInear amplification using Nonlinear Component
LNA	Low Noise Amplifier
LO	Local Oscillator
LSB	Least Significant Bit
LTE	Long-Term Evolution
LUT	LookUp Table
NCO	Numerically Controlled Oscillator
NF	Noise Figure
OCP	Output Compression Point
OFDM	Orthogonal Frequency Division Multiplexing
OIMD	Output InterModulation Distortion
OIP	Output Intercept Point
OPsat	Output Saturated Power
OSR	OverSampling Ratio
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PGA	Programmable Gain Amplifier
PDF	Probability Density Function
PFD	Phase Frequency Detector

PLL	Phase Locked Loop
PM	Phase Modulation
Psat	Saturated Power
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RF	Radio Frequency
RFIC	Radio Frequency Integrated Circuit
RL	Return Loss
RMS	Root Mean Square
RRC	Root Raised Cosine
RX	Receiver
RXFE	RX Front-End
SEM	Spectrum Emission Mask
SFDR	Spurious Free Dynamic Range
SiNAD	Signal to Noise and Distortion ratio
SNR	Signal to Noise Power Ratio
SSB	Single SideBand
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TE	Transverse Electric
TEM	Transverse Electromagnetic
TM	Transverse Magnetic
THD	Total Harmonic Distortion
TX	Transmitter
TRX	Transceiver
UE	User Equipment
VGA	Variable Gain Amplifier
VSWR	Voltage Standing Wave Ratio
WCDMA	Wideband CDMA
WSS	Wide Sense Stationarity
XM	Cross-Modulation
ZIF	Zero-IF

Nomenclature

t, τ	time variables
f	frequency variable
ω	angular frequency variable $(= 2\pi f)$
$x(t)$	continuous time signal
$x[n]$	discrete time signal
$X(f), X(\omega)$	frequency representations of $x(t)$ or $x[n]$
$\mathscr{F}_{\{x(t)\}}(f), \mathscr{F}_{\{x(t)\}}(\omega)$	Fourier transforms of $x(t)$
v, i, j	voltage, current, current density
$\mathrm{P}, p(t)$	in-phase, in-phase component
$\mathrm{Q}, q(t)$	quadrature, quadrature component
j	$\sqrt{-1}$
$\mathrm{Re}\{.\}, \mathrm{Im}\{.\}$	real part, imaginary part
$\vert.\vert, \arg\{.\}$	modulus, argument
$.^*$	complex conjugate
$\star$	convolution
$\delta(.)$	Dirac delta distribution
$\mathrm{U}(.)$	Heaviside unit step function
$x_\mathrm{a}(t)$	analytical signal associated with $x(t)$
$X_\mathrm{a}(f), X_\mathrm{a}(\omega)$	frequency domain representations of $x_\mathrm{a}(t)$
$\hat{x}(t)$	Hilbert transform of $x(t)$
$\hat{X}(f), \hat{X}(\omega)$	frequency domain representations of $\hat{x}(t)$
$\tilde{x}(t)$	complex envelope associated with $x(t)$
$\tilde{X}(f), \tilde{X}(\omega)$	frequency domain representations of $\tilde{x}(t)$
$\overline{(.)}$	time average value
$\mathbb{E}\{.\}$	stochastic expectation value
$\gamma_{x \times y}(t_1, t_2)$	cross-correlation function $\left(=\mathbb{E}\left\{x_{t_1} y_{t_2}^*\right\}\right)$
$\gamma_{x \times x}(t_1, t_2)$	autocorrelation function
$\gamma_{x \times x}(\tau)$	autocorrelation function in stationary case $\left(=\mathbb{E}\left\{x_t x_{t-\tau}^*\right\}\right)$
$\Gamma_{x \times x}(f), \Gamma_{x \times x}(\omega)$	power spectral densities of $x(t)$
$\mathbf{X}, \boldsymbol{X}$	vector, matrix
$.^\mathrm{T}$	transpose
$\Vert.\Vert$	Hermitian norm
$\cdot$	dot product
$\times$	cross product

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