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Digital Compensation for Analog Front-Ends

A New Approach to Wireless Transceiver Design

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Preface

The joint design of the analog front-end and of the digital baseband algorithms has become an important field of research for a few years because it enables the wireless system and chip designers to better trade the communication performance with the production cost. Unfortunately the existing designs apply this approach rather opportunistically to solve a well-determined problem. There is clearly a lack of a global approach.

The aim of this book is to propose a systematic approach to design a digital communication system. In particular, we will present how our methodology can be applied to the emerging wireless communication systems. As such, this book will be a valuable reference for wireless system architects and chip designers.

More generally, our book intends to be cross-disciplinary and to cover in detail the digital compensation of many non-idealities, for a broad class of broadband emerging standards and with a system approach in the design of the receiver algorithms. In particular, system strategies for joint estimation of synchronization and front-end non-ideality parameters will be emphasized. This approach is actually linked with the in-depth expertise that has been developed in the wireless research group of IMEC where the authors have spent many years and have been involved in projects covering the main broadband wireless standards.

The organization of the book is also very important to bring the reader up-to-date with the main topic and to assist him/her in gradually absorbing the important and vast material. We cover in the first chapter a detailed introduction of the emerging wireless standards, which is essential in understanding the rest of the book, followed in the second chapter by a detailed description of the front-end non-idealities. From this point, the reader is well equipped to understand what happens when the topics described in the first two chapters are merged, which is the goal of the third chapter. The last two chapters continue with an in-depth coverage of the estimation and compensation algorithms, first for a generic system to understand the methodology and details of the system approach, then for two main emerging standards to be more pragmatic and fully in line with the real world.

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Introduction

1.1 Wireless transceiver functional description

Emerging wireless communication systems are carefully designed to optimize at the same time the offered user capacity, the average spectral efficiency and the cell coverage. A set of complementary functions are successively implemented at the transmitter and at the receiver to support the communication while still respecting the power consumption and spectral occupancy constraints. Figure 1.1 gives a functional description of a typical wireless transceiver. Part of the functions are implemented on a digital processor (block (A) at the transmitter and block (D) at the receiver). The other part of the functions are implemented in the analog front-end (block (B) at the transmitter and block (C) at the receiver). In the following paragraphs, we give a synthetic description of the main transceiver functional blocks.

The *channel coder* adds structured redundancy to the bit stream at the transmitter that can be used at the receiver by the *channel decoder* to detect and ultimately correct the bit detection errors generated by various sources of signal distortion in the system. The *interleaver/deinterleaver* pair makes sure that the errors happen at random locations in the bit stream (bursts of errors are avoided).

At the transmitter, the *constellation mapper* converts the stream of coded bits into a stream of complex symbols. The necessary physical bandwidth is directly proportional to the symbol rate, so that high constellation orders are often foreseen to improve the system spectral efficiency. At the receiver, the stream of estimated symbols is converted back by the *constellation demapper* into a stream of estimated bits.

Most of the emerging communication systems rely on the orthogonal frequency division multiplexing (OFDM) technology (or on a derivative technology) to cope better with the channel time dispersion. The stream of complex symbols is organized in blocks of symbols (*serial-to-parallel converter*), that are possibly processed with the *linear pre-coder* and mapped with the *carrier mapper* onto a set of equally spaced sub-carriers in the frequency domain. The *inverse fast Fourier transform* (*IFFT*) transforms the blocks to the time domain and the *cyclic prefix* (*CP*) *adder* repeats part of the resulting blocks to make the transmitted signal appear periodic. Finally the time domain blocks of complex samples are converted to

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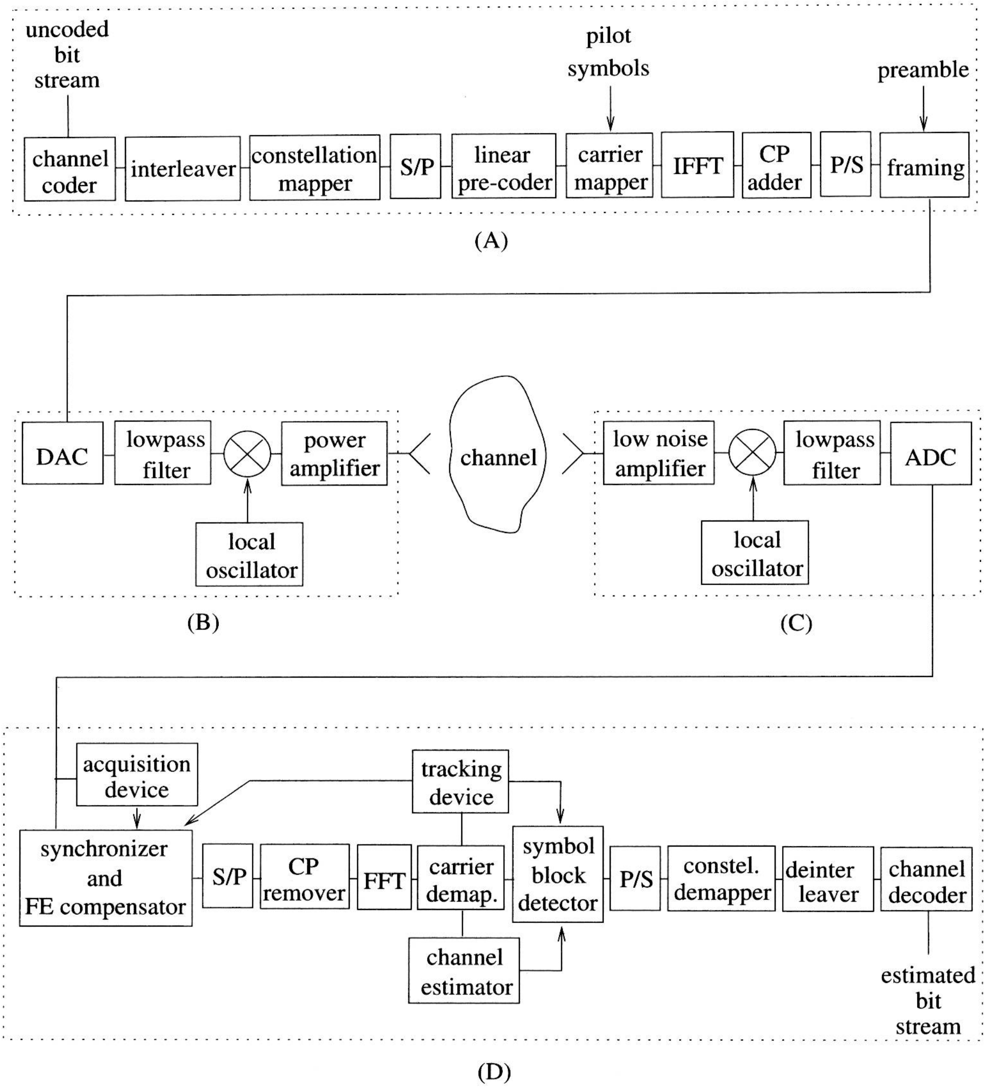

Figure 1.1 Wireless system block diagram: (A) transmit digital transceiver; (B) transmit analog front-end; (C) receive analog front-end; (D) receive digital transceiver.

a sequence of complex samples (*parallel-to-serial converter*). At the receiver, the counterpart of each operation defined at the transmitter is successively performed. In particular, the fast Fourier transform (*FFT*) brings back the signal to the frequency domain, where the time dispersive channel is seen as a multiplicative channel that can be compensated at a low complexity by the *symbol block detector*.

The functions described until now are all digital and therefore take a digital sequence as input/output. However, the signal sent over-the-air at the antenna can only be a time continuous signal. The role of the transmit analog front-end is to convert the sequence of complex samples into a time continuous signal sent at a pre-defined transmit power level within the allocated frequency range. The sequence of complex samples is first converted with the *digital-to-analog converter* into an analog signal, filtered afterwards with the *lowpass filter* to limit the signal to the desired frequency range, translated to the carrier frequency generated by the *local oscillator* with the *mixer*, and finally amplified to a sufficient power level with the *power amplifier*. The continuous signal received at the receiver antenna is first amplified with a *low noise amplifier* that adapts the signal power to the required receiver power input range, transported back to the baseband domain with the *mixer*, filtered with a *lowpass filter* to avoid aliasing when the signal is sampled in the *analog-to-digital converter*.

Before the communication can effectively happen, the receiver should be synchronized to the transmitter. The role of the *acquisition device* is to estimate the signal time reference and carrier frequency, together with some front-end parameters, based on a known *preamble* transmitted in front of the data burst. The error measured according to the transmitter reference is compensated during the *synchronization*. Because the acquisition is not perfect (noise corruption...), the remaining errors have to be continuously estimated in the *tracking device*. Known *pilot symbols* are often interleaved in the data symbols to support the tracking.

In this first description of the transceiver, we have clearly separated the digital and the analog functions. It should be mentioned, however, that some functions can be implemented either on the digital processor or in the analog front-end, or even shared between the two.

1.2 Evolution of the wireless transceiver design

Even if the digital transceiver and analog front-end were initially designed separately, there is today a clear trend to integrate the two designs in order to better trade the cost and power consumption of the final products. This section presents how the evolution of the wireless systems has triggered the development of a new field of expertise in the design of mixed-signal solutions.

1.2.1 Independent design of analog front-end and digital transceiver

Originally, the analog front-end and the digital baseband transceiver were designed separately. The role of the analog front-end was to down-convert the signal from the bandpass domain to the baseband domain. The role of the digital baseband transceiver was to demodulate the digital transmitted signals taking the effects of the propagation channel into account. Different competencies were needed for the design of the analog front-end and for the design of the digital baseband transceiver. Each of the two blocks was designed by assuming that the other block works ideally.

1.2.2 Low cost analog front-end

The desire to build lower cost analog front-ends has triggered the interest for a new domain of research. Indeed, by observing the impact of the analog front-end non-idealities on the received signal, it has been shown that some of them could be compensated digitally. As an example, the correlated part of the carrier frequency jitter causes a phase rotation on the received samples that could be estimated and removed from the received signal. Therefore, it is interesting to tolerate a certain level of non-ideality in the analog front-end, making it much cheaper, that can be compensated afterwards in the digital domain at a reasonable complexity. There exists a point of convergence between the analog and digital experts: they have to define together the specifications on the analog front-end (tolerable value of each non-ideality) making the optimal compromise between the cost of the analog components and the digital complexity of the compensation algorithms.

1.2.3 Higher system requirements

The emerging wireless communication systems employ higher bandwidths, higher constellation orders and multiple antennas to meet the new user needs. As a result, the system becomes more sensitive to the front-end non-idealities. For example, the difference between the lowpass filters on the I and Q branches becomes more pronounced, making the IQ imbalance frequency-dependent. Another example comes from the amplitude and phase mismatch between the different antenna analog front-ends. Therefore, the front-end compensation techniques should be designed carefully in the new communication systems.

1.2.4 Wish for software defined radios

Future wireless systems of the fourth generation (4G) will integrate different existing and evolving wireless access systems that complement each other for different application areas and communication environments. To enable seamless and transparent inter-working between these different wireless access systems, or communication modes, multi-mode terminals are needed that support existing as well as newly emerging air interface standards, thereby offering a trade-off between the data rate, the range and the mobility. A first approach to build a multi-standard terminal is to duplicate the analog front-end. It is therefore clear that the cost of each analog front-end becomes critical and that the techniques to compensate the front-end non-idealities are required to limit the cost of the overall system. A second approach to build a multi-standard transceiver is to construct a flexible analog front-end. By tuning a set of parameters, the analog front-end will support a given communication mode. Once again, flexible analog front-ends are very costly and all efforts should be made to reduce their cost. Therefore, the digital compensation techniques of the non-ideal analog front-end are also needed.

1.2.5 Technology scaling

Much effort is spent today in the minimization of the production cost and power consumption of the new hardware platforms. In line with this trend, the dimension of the transistors is ever decreasing. Unfortunately, the scaling of the technology also brings new challenges in terms of analog front-end non-idealities. As the supply voltage decreases when the dimension of the transistors is reduced, the dynamic range is limited and the level of non-linearities increases. The behavior of the components is also less predictable due to their increased variability. On the other hand, the computation power of the digital platforms is improved and more complex front-end compensation algorithms are enabled.

1.3 Contribution of the book

The joint design of the analog front-end and of the digital baseband algorithms becomes more and more popular in the literature. Unfortunately the existing designs apply this approach rather opportunistically to solve a well-determined problem. There is clearly a lack of a global approach. The aim of this book is to handle the problem globally by proposing a systematic approach to design a digital communication system. This section explains the three major objectives targeted in this book.

1.3.1 Low-cost analog front-end

The primary goal of the book is to describe how the non-idealities introduced by the analog front-end elements can be compensated digitally. As an example, the phase noise (or carrier jitter), caused by the inaccuracy of the local oscillators, and the IQ imbalance, caused by the difference between the analog elements on the I and Q branches when analog frequency down-conversion is applied (zero-IF architecture), will be considered. By doing so, the specifications on the analog components can be relaxed and the overall analog front-end can be made at a lower cost.

1.3.2 Integrated system strategy

The book presents the joint strategy for the front-end compensation, channel estimation and synchronization. The different non-idealities are estimated, often based on known sequences of transmitted symbols, and compensated afterwards. The non-idealities can be first estimated based on a preamble sent at the beginning of a physical burst, used also for the mobile terminal coarse synchronization (time and frequency) and for the channel estimation. Another possibility is to estimate them by means of pilots sent simultaneously with the information symbols, used also for the tracking of the synchronization errors and channel changes over the time. It is therefore important to integrate the estimation and the compensation of the non-idealities with the synchronization and channel estimation algorithms. Because each system has its own requirements, the strategy for joint front-end compensation, channel estimation and synchronization is specific to the system under interest.

1.3.3 Emerging wireless communication systems

In this book, we will study how the transceivers can be designed for emerging wireless communication systems to enable the compensation of the analog front-end. The methodology will be applied to the emerging wireless local area network (WLAN) and cellular communication systems:

- As for the WLAN communication systems, the IEEE 802.11n will be studied. It is the multiple antenna extension of the existing WLAN IEEE 802.11a/g based on OFDM.
- As for the cellular communication systems, the 3GPP LTE will be investigated. It targets much higher data rates than the third-generation cellular communication systems under much higher mobility conditions. A hybrid air interface has been selected: the downlink will be based on OFDMA and the uplink will be based on SC-FDMA to lower the constraints on the mobile terminal power amplifier.

1.4 Organization

We will first present the main air interfaces that are emerging in the wireless communication systems and summarize their properties. Second, a model of a non-ideal analog front-end is introduced, based on which the impact of the non-idealities on the performance of the air interfaces will be evaluated. The methodology to estimate and compensate each non-ideality will be explained by considering a generic communication system as a reference for the sake of clarity. Afterwards, the methodology will be extended to the emerging IEEE 802.11n and 3GPP LTE communication systems.

- The most promising air interfaces for the emerging wireless communications systems will be introduced in Chapter 2. For each air interface, a simplified block diagram of the system will be provided, based on which a mathematical input/output relationship will be built. The major principles will be explained (frequency domain multi-path channel equalization, spatial diversity with multiple antennas . . .). Finally, the air interface will be integrated in the most adapted communication system (WLAN or cellular) and reference performance curves will be provided.
- In Chapter 3, typical super-heterodyne and direct down-conversion front-end architectures will be introduced, and extended to multiple antennas. Based on that, the constituent blocks will be investigated and their non-ideal behavior will be characterized. Finally, a mathematical description of the different non-idealities will be provided, based on which a front-end model can be built.
- The impact of the non-idealities on the different air interfaces will be studied in Chapter 4. For each non-ideality, an analytical description will be provided (impact on the constellation, error distribution) and a numerical analysis will be performed. We will look into the individual impact of the carrier frequency offset, the phase noise, the sample clock offset, the clock frequency jitter, the IQ imbalance, the clipping and quantization and the non-linearities. Afterwards, we will investigate the effect of the non-idealities when they are introduced jointly in the system. In the case of multi-dimensional systems (multiple antennas and multiple users), we will evaluate the inter-stream interference generated by the different effects. The impact of the mismatch between the different branches (amplitude and phase mismatch between the different antenna or user front-ends) will be further presented.
- The aim of Chapter 5 is to describe our methodology based on a generic wireless communication system. The generic communication system will be similar to a single-antenna WLAN system based on OFDM. We will first present the structure of the frame based on which the different steps can be performed and afterwards describe all the steps in turn (burst detection and AGC, packet arrival time estimation, carrier frequency estimation, IQ imbalance estimation, carrier frequency offset and IQ imbalance compensation, tracking).
- In Chapter 6, the methodology proposed in the previous chapter will be applied to the emerging communication systems, in particular, taking into account the constraints from each system configuration. First, the multiple antenna WLAN IEEE 802.11n communication system will be considered. Second, the high-mobility long-term

evolution of the 3GPP cellular system will be studied. The frame structure of both systems will be described, and the estimation/compensation algorithms necessary to mitigate the system specific effects will be presented.