Wireless Transceiver Systems Design
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Preface

During the last 30 years, wireless\textsuperscript{1} in communications has grown from a niche market to an economically vital consumer mass market. The first wave, with the breakthrough of 2G mobile telephony focused on speech, placed wireless communication in the consumer mass market. In the current second wave, services are extended toward true multimedia, including interactive video, audio, gaming, and broadband Internet.

These high-data rate services, however, led to a separate IP-centric family of wireless personal (WPANs) and local area networks (WLANs) outside the 2G/3G mobile path. Since diversity between data- and voice-centric solutions and the competition between standardized and proprietary approaches is today more blocking than enabling effective development of successful products, a third major wave is unavoidable: a consolidation of both worlds in portable devices with flexible multistandard communication capabilities enabled for quality-of-service-aware multimedia services.\textsuperscript{2} At the same time, the dominance of wired desktop personal computers has been undermined by the appearance of numerous portable and \textit{smart} devices: laptops, notebooks, personal digital assistants, and gaming devices. Since these devices target low-cost consumer markets or face wired competition, time to market is crucial, designed-in flexibility is important, low-power operation is a key asset, yet device cost shall be at a minimum.

This book approaches this \textit{design tradeoff} challenge from the perspective of the \textit{system architect}. The system architect is concerned both in an efficient design process and in a competitive design result. Already with the advent of the second-wave high-rate communications, traditional design techniques, relying on early partitioning and substantial engineering margins per design domain, hit the red-brick wall of design efficiency and product cost. We present solutions to the two central design challenges: how to efficiently design a second-wave WLAN system and how can we prepare already for the upcoming challenges of flexible multi-standard terminals? Consequently, we illustrate true crossdisciplinary electronic system-level design with examples in algorithm–architecture codesign, mixed-signal algorithm/architecture codesign, and crosslayer system exploration. Three recurring themes distinguish this work: preference for scalable and hence reusable architectural concepts, proof of concept through actual design and experimental verification, and consequent analysis of design steps and their development into a methodology.

\footnotesize
\textsuperscript{1} Traditional broadcasting-only services such as radio or TV distribution are excluded.

\textsuperscript{2} In IMEC, the term M4 for multimode multimedia was coined for this communication and service paradigm. Outside, the term 4G is often used but sometimes also 5G.
The research described here is based on the Ph.D. dissertation of the author which took place mainly between 1998 and 2003 at the Interuniversity Microelectronics Center (IMEC), an independent large-scale research center for micro- and nanoelectronics and its applications in Leuven, Belgium.

Our research resulted in the world’s first two low-cost and high-performance OFDM baseband ASICs for wireless LAN, practical solutions for mixed-signal acquisition, digital front-end nonideality compensation, and application-driven transceiver design.

Concerning design methodologies, we developed a practical digital and mixed-signal design flow, contributed to behavioral modeling, cosimulation and design technology, and extended the multiobjective optimization paradigm to a practically applicable design–calibration–run-time approach as well as showed its suitability in the mixed-signal architectural and crosslayer domain.

This book is not focusing on the latest modifications and adaptations in the quickly emerging world of standards around WLANs. Instead, it aims at capturing the design challenges, decision-taking processes, and crossdisciplinary aspects of designing complex transceiver systems in the wireless domain and proposing generic ways of addressing these challenges. This is at the heart of the tasks of a system architect which in the era of system on chip (SoC) coincides more and more with the one of a chip architect.
Acknowledgments

This book has emerged from my Ph.D. dissertation at IMEC/KU Leuven. So, most acknowledgments go into that direction. However, the way that Ph.D. project started and the way it moved on is an integral part of the story. To understand the motivation behind the Ph.D. work and ultimately behind this book, it may be necessary to know more than the purely technical aspects of designing wireless LANs. Hence, I want to disclose some of it to the reader of this book.

Going for a Ph.D. is always striving for the creation of something new: groundbreaking results and major contributions to the state of the art. Definitively, but it is not also about crossing traditional research boundaries, challenging discussions, and fruitful work with other people. So it would not be poor if we only looked at the endpoint of the story and not at the travel itself?

To begin with, this thesis was not born as the child of a “normal” Ph.D. student’s life, which starts with a supervisor and a nicely defined focused topic, with a scholarship, all in a familiar environment, and a birth after 4 years. Rather, it has been a 6-year journey, starting with a sudden move to Belgium. What followed turned out to be a tricky balancing act between industrial projects and scientific publications, between teaching and project organization, a walk across different groups, and meandering along the chasms of analog and digital, systems and components, implementation and methodology. It has been an adventurous quest, an all-inclusive trip with pain and joy, and the simple conclusion that I would not want to miss anything from it, after all.

Particularly, I will never know how to thank all the people that made this journey fruitful and interesting. Still, I will make a try, so let us dig into the roots of how it all started…

Back in Germany

It would have never happened this way, I had not followed the vivid lectures of Prof. Robert Maurer† on RF communications and microwave design back in Germany. All of a sudden, my eyes opened up for the wide world of wireless communications, of microwave and RF, of analog and digital. Add to this the overwhelming experience of 3 years part-time work in a great atmosphere at the Institute for Biomedical Engineering, which made engineering put in a perspective to the realms of biology and medicine. Thanks to them the ground was paved for my interest in personal wireless communications systems.
IMEC comes into the picture
My diploma in reach (not yet in my pocket), a thesis on wireless LAN for biomedical applications just behind me, and an invitation for an interview based on a brief e-mail sent before Christmas 1996, I arrived in Leuven on a cold day, even with snow (quite exceptional these days) in the corners of the parking. While having no experience in microelectronics and applying for a job as “wireless expert in ASIC design,” destiny appeared in the form of Bert Gyselinckx, Marc Engels, and Ivo Bolsens who put an incredible amount of trust into me and offered me to join the WISE group. Fortunately, I soon got company on my journey through the wonders of wireless LANs, when Liesbet Van der Perre joined a few weeks later. I still remember her saying “Proof is the bottom line for everyone” and our first bottles of champagne for the Festival ASIC.

Well, where is the Ph.D. starting in the end?
The inspiring talks of Prof. Hugo De Man illustrating the challenges of system-level design and expressing the crucial need for crossdisciplinary research grew the idea for a broad, system-level and both design- and methodology-oriented thesis: mixed analog/digital exploration and design for wireless broadband transceivers. A start had been made already with the digital VLSI designs of Festival and Carnival. As the topic suggested, revolution instead of evolution was the way; hence I moved with my new focus into the mixed-signal and RF applications group to complete this work. I owe invaluable appreciation to my promoters Prof. De Man and Prof. Georges Gielen for their inspiration, scientific criticism, and support during my Ph.D., and to Marc Engels, Stéphane Donnay, Gerd Vandersteen, Piet Wambacq, Liesbet Van der Perre, and Bert Gyselinckx for their patience and help, for suggestions, reviewing, and proofreading.

You never work alone
Research is a path that you do not walk alone and it particularly means that you never work alone either. My thanks go to all people I enjoyed working with and learning from: Veerle and Alain for telling me what digital design is about en voor een warme ontvangst die mijn taalkennis Nederlands zonder twijfel bevorderde. Thanks also to Geert, Mario, and Mustafa during the busy days of Festival and Carnival tape-outs. For the algorithmic side of life, my thanks go to Patrick, Steven, Luc, Frederik, Huub, and Andrew; for occasional demo highlights and nightmares to Roeland (2×), Tom, Mike, Bhasker, Peter, and Maryse. Moreover, thanks to Patrick, Luc, Radim, and Erik for being incredibly patient with respect to OCAPI bells and whistles. Thanks to all former MiRA people for providing me a nice welcome in 2000 and a steady home and especially for the open discussions and their CAD support to Michaël, Petr, and Gerd. Particular thanks to Björn, Joris, Hideki, and Guido. Who did I forget? Indeed, Boris, for having a great time, tough discussions, and for bringing me always down to earth when dreaming in

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3 In fact, this work centered around body area networks which, since 2003, have been receiving significant scientific attention. In those days of 1996, it may not have been the right time yet but this is another story.
the Pareto space. In this space, I enjoyed adventures together with Bruno, Sofie, Francky, and Gregory. Many thanks go also to Wendy and Yves at the VUB ELEC lab for real measurements. I also enjoyed a great time as their daily thesis advisor with Mario, Ludwig, and Roeland. I guess I would better stop here and now before I have addressed everyone in DESICS individually. So, last but not least, many thanks to Annemie, Karine, and Myriam for their warm help and support.

Numerous contacts with industry provided me with an amazingly rich amount of feedback. Particular thanks for vivid discussions and permanent challenging, for their technical support, for bottles of champagne and their appreciation of our work goes to National Semiconductors. Thanks also to project partners at Motorola Genève, Infineon Technologies in München and Villach, ST Microelectronics in Pavia, and Sony Japan for their interest in and feedback on my work at IMEC. Finally, I would like to express my gratitude to everyone at Resonext Communications for a great time in the hot phase of a startup endeavor, particularly to Jess, Karl, Farbod, Patrick, and Radim. I am very grateful to Marc, Bert, and Stéphane at IMEC and David and Morteza at Resonext for offering me this unique opportunity.

Friends at work

Besides work, there are other good reasons to spend time together with your colleagues. So, floorball comes into my mind. Having started with only a handful of people in the good old VSDM days in late 1999 – it must have been one of those rainy autumn sunsets – things have grown and this sport still gathers quite some people every week. This was a welcome activity complementing office life and providing a good balance for the, sometimes, unavoidable deadlines, weekend and evening work. I have made numerous friends with people working throughout whole IMEC and outside of IMEC, a truly unforgettable experience and one of the reason why I simply love this place and its people.

My greatest gratitude goes to my mom and dad, who always trusted in me, helped me on whatever way I had chosen and supported my sudden decision in January 1997 to leave for Belgium: Von Herzen-vielen, vielen Dank für Eure Unterstützung. I would like to devote this book to both of them.

Leuven Wolfgang Eberle
October 2007

4 Now Freescale Semiconductor.
5 In the meanwhile, Resonext Communications have been acquired by RF Micro Devices (RFMD).
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1 Introduction

You see, wire telegraphy is a kind of very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. Do you understand this? And radio operates exactly the same way: you send signals here; they receive them there. The only difference is that there is no cat.
Albert Einstein, 1879–1955.6

A problem well stated is a problem half solved.
Charles F. Kettering, 1876–1958.6

This work reflects the research process and its results that the author has obtained concerning functional and architectural system design and design methodology for high-data rate wireless local area networks (WLANs). In this context, functional design aims at achieving a particular transformation of inputs to outputs independent of implementation and hence cost constraints. Architectural design focuses on the efficient realization of input/output transformations constrained by available technology constraints. We approach the entire design process from the perspective of a system architect.

Our main contribution is a structured approach to wireless transceiver design, which aims at enlightening the traditional black box of system design into a structured gray, ultimately white box. The traditional approach of early partitioning of design tasks according to disciplines, such as analog or digital, functional or architectural, physical or higher OSI layers, has over the years resulted in a huge design efficiency gap and intolerable accumulating design

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6 Clearly showing Einstein’s inventiveness and spirit, this explanation raises more questions than it answers. For sure, Kettering would have said that Einstein’s view on it was great but unfortunately of no worth to get on to a pragmatic solution. Ever striving to get his new ideas transferred into reality, he pushed development as a cooperative team effort. But, with Kettering’s words, both would have agreed that “research is a high hat word that scares a lot of people. It needn’t. It is rather simple. Essentially, research is nothing but a state of mind – a friendly, welcoming attitude toward change.”
margins. Unlike in traditional design, we treat functional design, architectural design, and design methodology in a joint, crossdisciplinary manner (Fig. 1.1).

Our approach leads, first of all, to a better understanding of the design tradeoffs involved in wireless design; in a second step, this awareness enables us to propose better functional and architectural solutions and a more efficient design flow. We use high-data rate WLANs as a real-world driver application to illustrate our approach; yet, most solutions were conceived to scale such that the underlying principles can be reused in the design of future multistandard multimedia transceivers.7

Fig. 1.1. Three components of the design of integrated systems are jointly treated

Particular contributions to the state of the art were achieved in each of the three domains. On the functional side, novel algorithms were conceived for the acquisition, mixed-signal front-end compensation, equalization, and tracking process in packet transmission. On the architectural side, a baseband processor architecture for OFDM has been proposed that efficiently accommodates the functionality mentioned before, introduces some energy–performance scalability features, and integrates neatly both with analog front-ends and the MAC/DLC layer. Finally, design technology has been developed to support the efficient exploration and design of functional, architectural, mixed-signal, and crosslayer design.

This introductory chapter is structured as follows. Section 1.1 sets the scene with a description of current wireless broadband communications and its evolution to integrated multimode multimedia devices. Section 1.2 focuses on the design process for such a wireless local area transceiver, which results in the situation and motivation of our work. Section 1.3 sets clear objectives and details the methodology we followed to approach them. Section 1.4 gives an outlook on the contents and structure of this work and puts forward our contributions to the state of the art.

7 In the most general case, we require a multiband, multimode, and multifunction transceiver [Wiesler01]. Since standardization often covers both band and mode requirements, we refer to the first two criteria as multistandard.
1.1 Context

Wireless communications today has become a mature field, yet it still faces tremendous growth rates and continuously enters new markets. A mix of new service ideas together with technology awareness and exploitation of the cost benefits in an economy of scale seems to have created a perpetuum mobile.

Widespread usage appeared when the introduction of 2G mobile telephony pushed mobile phone usage from 10 million subscribers in 1990 to an estimated 700 million in 2001 and an expected 2 billion in 2007 [Rappaport02]. Originally, the breakthrough of 3G deployment was expected for 2004, which, after about 10 years of development, will enable the transition from voice to data traffic and from data rates of 9.6 kbps for 2G to 384 kbps for high mobility and 2 Mbps for reduced mobility [Ojanpera98]. However, a combination of technical challenges and difficulties in clearly positioning this technology in the marketplace has not yet led to widespread deployment by now. These mobile standards establish a cellular layer in the range-data rate plane (Fig. 1.2), exhibiting a clear trend toward higher data rates.

A similar evolution toward higher data rates has taken place in the field of distribution and broadcasting, e.g., through a family of digital video broadcasting standards [DVB-T, DVB-H] for suburban and rural coverage, and stationary wireless access schemes for urban coverage [Honcharenko97, Eklund02].
shorter distances up to 100–150 m, WLANs appeared. WLANs emerge as a hot-spot layer to fill the gap for higher data rates and high network density in indoor and campus environments, which could otherwise overload cellular infrastructure. For even shorter distances, notably inside the same room or in the aura of persons, a family of WPANs came up [Gutierrez01] and ultra-wideband (UWB) solutions were proposed. Recently, WiMAX [IEEE802.16] and mobile WiMAX [IEEE802.16e] have been developed to extend area coverage and higher mobility, respectively. Next to the development of solutions for specific applications such as short-range broadband, we notice a general trend – summarized in the terms “beyond 3G” or “4G” – that aims at higher efficiencies, getting closer to the capacity/power bound.

In general, we can observe that both an increase in range/mobility and in data rate lead to higher system complexity and hence power consumption; portable devices avoid the empty spot at the upper-right corner of the design space where the gain in system capacity density becomes prohibitively low and/or power consumption exceeds operation specifications of portable devices.

Our research has primarily focused on wireless LANs for indoor and campus operation. They originally emerged from the DECT standard, which from 1992 on was mainly used for cordless telephone applications [DuttaRoy99]. Later on, ETSI and IEEE standardization bodies started separate initiatives for wireless LAN standards: the HiperLAN and IEEE 802.11 families, respectively. Early versions suffered from higher costs and lower data rates compared to their wired Ethernet LAN counterparts and could only move into markets where mobility or convenient ad hoc installation was a key; with the no-new-wires paradigm, the medical care, campus networks, conferences, and warehouse logistics could be entered [Rose01]. A breakthrough was only possible through placement in a consumer market. The idea of networks for home was born but has put an even higher pressure on manufacturers to design low-cost and easy-to-use WLAN products within a sufficiently short time to market [DuttaRoy99, Rose01]. Today, everyone can buy WLAN terminal and access points in supermarkets; more and more hot-spot locations appear where people can enjoy wireless LAN access while sitting in a café or walking in a shopping mall. Companies change their infrastructure and WLAN is on the verge to become a standard component of cell phones like Bluetooth became for short-range communication. While sales grow, chipset prices are dropping from $20 in 2002 over $8 in 2003 to about $4 in 2004 and expected $2 in 2006 [Wheeler03, Merritt03].

So, what is next? Parallel evolution paths have established a multilayer structure (Fig. 1.3). Next-generation 4G communication systems will benefit from vertical handover between these layers [Mohr00], selecting the most appropriate end-to-end route through the available networks to provide the user with desired quality

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8 For a more detailed view, we refer to Chap. 3.
9 Intel: “a cheap way of connecting,” Boingo Wireless: “a standard component of cell phones,” and Qualcomm: “we are on standby when requests come from carriers.”
of experience (QoE). Due to the enormous difference in requirements across the range-data rate plane, the appearance of a single, flexible standard is very unlikely. Instead, future terminals will have to flexibly cope with multiple transmission techniques as diverse as single carrier and multiple carrier, single antenna and multiple antenna, CDMA or TDMA.

This integration of multiple modes and standards into a portable device represents a major increase in design complexity. For 2G and 3G systems, a 10-year cycle between research and successful market appearance seems appropriate [Raivio01]. Still, the introduction of 3G faced such a large amount of, also technical, problems that the original term “beyond 3G” [Steele00] has been deliberately replaced by the less biased 4G or even 5G [Raivio01]. It appears beneficial to learn from the difficulties that the introduction of 3G mobile faced and compare them to the important points for the success of wireless LAN:

- Achieving substantially higher rates than the previous generation and sufficiently high for relevant applications and services is crucial.
- Providing a sufficiently open communication system relying on a layered approach such as IP is beneficial to meet time-to-market constraints and foster development of services.
- Delivering low-cost devices on-time, preferably from multiple manufacturers, is a key concern.
- Exploiting shared unlicensed frequency spectrum which avoided the high financial cost and risk that have been introduced by governments when auctioning spectrum for 3G operation.

We can conclude that the current wireless communications scene offers a tremendous potential for growth in consumer markets; the required increase in data rates and the move toward more flexible multistandard devices, however, results in a severe performance/cost dilemma. Moreover, the current explosion in standardization activity and the needs for multistandard devices push for a fundamental increase in exploration and design efficiency to meet time-to-market constraints. Essentially, the gap between abstract service and communication concept definitions and their concrete implementation in products has never been as wide as today.

### 1.2 Motivation and Objectives

In fact, Sect. 1.1 sketched the wireless evolution over the last 15 years until 2005. Obviously, the initial motivation for this research work must be found at its beginning. Hence, back to the concrete situation in 1997.

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10 The term *QoE* is defined in Chap. 3; it could be roughly described as quality of service (QoS) perceived by the user.
As early as 1996, Harris Semiconductor\textsuperscript{11} had introduced its first PRISM chipset for spread-spectrum-based wireless LAN at 1–2 Mbps which turned the company later into the leading provider of 802.11b chipsets [Harris96]. The InfoPad multimedia terminal at UC Berkeley had a similar focus with a 1–2 Mbps peak data rate for the downlink but a low 64–128 kbps asymmetric uplink only [Truman98]. However, 1–2 Mbps neither could compete with the wired 100-Mbps Ethernet solution nor could these data rates support true multimedia or compete in the business and office market. There was only very little preliminary work existing on the combination of OFDM in a WLAN context [McDermott97]. Their focus on discrete board-level design, initially 40-GHz carrier frequencies and picocells, using only 16 subcarriers and a spectrally inefficient DQPSK modulation left considerable room for our research.

This situation represented a common starting point for two study paths at IMEC: one was to explore theoretically algorithms and techniques for a further increase in data rate [Vandenameele00, Thoen02a] and the other was to look for solutions to close the design gap between theory and practice. We adhere to the second approach. We jointly assumed, for overall infrastructure cost reduction, a microcellular approach for indoor and campus environments relying on moderate RF frequencies in the 2–6 GHz range, and the need for a significant increase in data rates into the 100-Mbps range.

Not uncommon to new trends and markets, skepticism was present in 1997 on whether wireless LANs with high-data rates could be designed for sufficiently low cost and power consumption. The recent spread-spectrum-based 1–2 Mbps products and the 11-Mbps 802.11b proposal being in an early standardization phase in these days, turned down chances for a high-rate proposal based on a fairly unknown technology such as OFDM. Over time, with prior advancement in the design, three of these fundamental roadblocks appeared at the application side:

1. The wireless world in 1997 was – to a large part – focused on single-carrier transmission schemes. Industry was yet to be fully convinced that digital solutions could really enhance and replace significant parts of their analog transceiver designs. Despite promising forecasts for OFDM [Bingham90], many feared the complexity of large-size FFTs such as in the upcoming DAB or DVB-T work [Bidet95]; another challenge to overcome was the need for novel solutions for practical problems such as channel estimation, signal acquisition, and synchronization [Meyr98]. Proof was needed that an efficient digital solution would be feasible in the wireless LAN context.

2. Once digital complexity was mastered, skepticism focused on the analog/RF front-end part of the wireless LAN. The need for high-performance front-ends to cope with OFDM would unavoidably lead to

\textsuperscript{11} Harris Semiconductor was spun off as Intersil Corp. in August 1999 and divested its WLAN business to GlobespanVirata in August 2003.
high-cost and high-power consumption [Martone00]. At that time, evidence was yet to bring that digital compensation techniques had the capability of relaxing front-end specifications and increasing the performance at negligible additional cost.

3. While these first two steps may have improved performance, a link analysis revealed that the transmitter, more notably the power amplifier, represented a major power consumption bottleneck [Raab02]. This is partly due to the fact that transmitters have been *traditionally* designed for worst-case conditions and basic class-A power amplifier topologies are the rule. We strive for solutions to reduce the average power consumption following three approaches: scenario analysis, power control [Ebert99], and DSP-controlled power amplifier usage [Asbeck01].

Inherent in all three suggestions, we find the need for crossdisciplinary design: at the algorithm–architecture, analog–digital, and crosslayer system–component level. Unfortunately, joint treatment of multiple domains imposes a significant increase of design complexity to the designer. This can only be resolved in a structured way through methodology and, eventually, design technology and computer-aided design (CAD) tool support. In particular, two challenges can be identified that, together with the previous three, establish a total of five challenges that we will address:

4. Design technology for architectural design and design refinement at the physical layer,12 be it algorithm–architecture or analog–digital, is required for the DSP core and the suggested digital compensation techniques are needed both at transmit and receive side. While appropriate solutions have become available, e.g., for HW/SW codesign [Bolsens97], the mixed-signal threshold has not been sufficiently reduced despite some positive signs as early as 1994 [Halim94]: both the SRC and MEDEA consortia keep mixed-signal design listed as a significant research gap [SRC00, MEDEA02, MEDEA05].

5. Multimode capability and the move toward multistandard solutions increase the need for application and design space exploration. Already for WLAN, it could be shown that some modes in the standard are redundant [Doufexi02], while inflexibility at other places diminishes performance [Asbeck01]. Again, methodologies were lacking that enable a system-wide, mixed-signal exploration to establish a balanced, performing and cost-efficient, flexible design [SRC00, MEDEA02, MEDEA05].

It becomes obvious why, given this amount of unanswered questions already for plain OFDM, we decided to center our work at applying OFDM for WLAN. Extent-

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12 The physical layer of the OSI networking layer scheme is meant here, *not* physical design.
sions such as multiple-antenna techniques, adaptive loading, or advanced coding techniques have not been treated in our work, but are currently studied by others.

Importantly, most questions arose around the joint design of the analog or digital signal processing functionality. A look at the OSI networking layering scheme for wireless LAN explains this fact (Fig. 1.3). Established in the telecommunications field with seven layers ranging from the application down to the physical layer, the IP-centric data communications world separated the stack into an application-oriented top and a transport-oriented bottom part. Contrary to the telecom world, both parts are treated in a largely independent way, such that wireless LAN itself only introduces new layers at the L1, L2a, and L2b layers. For the rest, it relies on existing IP and other standardized application protocols.

Fig. 1.3. In the OSI layering scheme, we treat both aspects in the user/control plane as well as in the management plane. Our main focus is on the lower layers (L1–L2a) with the inner transceiver as a starting point. In the system exploration, we also take into account different service and application requirements (L7). The shaded areas denote our involvement on QoE RRC, AL, MAC, and PHY.
The OSI scheme distinguishes between the user and the control plane, which are strongly layered, and a nonlayered management plane. In packet-oriented wireless LAN, user and control plane share equal or similar semantics and are hence treated together; they take care of user information transfer and the setup and maintenance of connectivity. The management plane includes radio resource control (RRC) and exchange of resource information between layers and network resources; it is there where total user QoE is enabled.

When we map the questions to the appropriate layers and planes, three foci are recognized: the L1 and L2a layer user/control plane for digital and analog signal processing, the management plane for QoE-aware crosslayer RRC, and the application layer which provides QoE constraints based on application and user requests.

Finally, we can summarize the objectives of our work: we will propose adequate solutions to the five previously mentioned challenges. In the context of OFDM-based 2G wireless LAN and similar future flexible broadband transmission schemes, this means:

- Developing functionality and scalable architectures enabling a low-cost low-power implementation including the mitigation of all relevant practical nonidealities
- Establishing a mixed-signal exploration and design flow that enables an efficient process for this design task, ultimately speeding up time to market

1.3 Approach

Having stated the objectives of this work is the necessary entry point for the discussion of how we are approaching a solution.

A key aspect for an efficient development of new architectures and methodologies is a concrete functional application driver with accompanying product constraints. In our case, the driver is wireless LAN and the constraint is the implementation in low-cost low-power terminals. All results will be judged regarding their usefulness for this driver. Moreover, aware of the flexibility requirements for future systems, we also assess the scalability of our solutions; in general, we will favor scalable and modular solutions.

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13 This section is sometimes titled “methodology.” We prefer approach over methodology since approach actually refers to a particular mindset rather than the term methodology that, originally, relates to a body of practices, procedures, and rules. This distinction is taken up again in Chap. 2.
As a system designer, addressing this goal with a pure top-down approach seems intriguing. However, limited knowledge on the application and constraints prevents him or her from doing so. Motivated by the classical divide-and-conquer approach, we propose here to start from a core problem and, incrementally, add more and more context to it. Which context is added depends on a selection process that determines its criticality to the final system. This results in a mixture of a top-down selection, bottom-up modeling, and top-down decision process, on which we will elaborate more in Chap. 2.

A fundamental difference between engineering and art in general is that engineering should develop and follow a methodology through which an increase in design efficiency is obtained in repeated or similar derived designs. Hence, we carefully analyze each design step and place it in a design flow. Design steps which appeared critical in design time or error-prone in the hands of a human designer were taken up for the development of CAD technology.

Clearly, from these assumptions, we expect different results than from the approach in canonical dissertations\textsuperscript{14} on algorithms, architectures, or design technology. When comparing our approach to those commonly applied in dissertations, we recognize three major differences.

First, the system scope will not lead to optimal component or algorithm design in the classical sense under narrow conditions. Instead, an operational system will be the result and favoring scalable and modular solutions will guarantee its reuse with extended requirements. Consequently, noncritical components will not be optimized further than necessary.

Second, the focus on the numerous system-level challenges prohibits spending significant effort on, e.g., circuit-level techniques. Instead, scalable and modular architectural solutions will be proposed with clear interfaces and boundary conditions such that, e.g., circuit-level techniques can still be applied independently.

Finally, we try to establish a mixed-signal design flow and prove its benefits in a world still deeply divided into analog or digital and algorithms or architectures. Intentionally, our effort was concentrated on a crossdisciplinary design methodology only; in all other cases, we suggested interfacing with experimental or commercially available tools. Our goal is not to provide design technology within one domain.

\textsuperscript{14} Remember that a Ph.D. dissertation lies at the base of this work. The majority of Ph.D. theses address localized problems where deep exploration of a particular problem or class of problems is desired.
1.4 Preview of Contents and Contributions

This section introduces the structure and conceptual flow of this book. This introductory chapter represents the first of, in total, eight chapters. The discussion of a variety of design and design methodology aspects at different applications and abstraction levels calls for a particular structure for this text to enable quick access both to general ideas and detailed information (Fig. 1.4). We aimed at a clear, formal separation of functional/architectural design on the one hand and design methodology/technology on the other hand.

Chapters 3–6 focus on the design aspects for the WLAN driver case, extending its functional and architectural scope from a general specification over a single design aspect toward the system level. These four chapters are embedded in a design process by Chaps. 2 and 7; the first introduces its requirements and philosophy, the latter details the developed design technology (DT) and our...
experiences during its application to the WLAN design driver. As illustrated, design and design methodology (DM) were, in practice, codeveloped.

Chapter 2 focuses on the design process and methodology challenges apparent to the design of integrated wireless communications systems. It motivates and situates the functional and architectural research work in Chaps. 3–6 in a design flow. We stress that only a structured, crossdisciplinary approach in design can reduce the design efficiency gap and pave the path for wireless terminals with appealing performance–cost properties. Two techniques have been addressed in particular: first, the consequent codevelopment of design and design technology to increase design efficiency; second, the systematic multiobjective exploration and partitioning of a design into design-time and run-time aspects to reduce product cost for the same performance:

- The importance of a crossdisciplinary approach to wireless system design has been motivated and illustrated in [Eberle02c, Eberle02e, Verkest01a, Bougard03a].

Chapter 3 introduces WLANs as particular application driver, which is used throughout the entire book to analyze actual design issues and prove both our proposed design and design technology solutions against a practical case. Since system design, as a true engineering discipline, is mainly concerned with living up to its numerous constraints, we will briefly review constraints coming from standardization, business, application, technological, and physical constraints. We motivate three system-level assumptions: a microcellular approach to wireless LAN, the need for a significant increase of peak data rates from existing 1 Mbit s\(^{-1}\) to about 100 Mbit s\(^{-1}\), and the importance to include flexibility and quality-of-service (QoS) awareness for multimedia applications:

- The microcellular networking scheme appears in [Eberle97a, Eberle97b]. A substantial increase in data rate by two orders of magnitude is recommended in [Engels98, Gyselinckx98]. Multimedia applications as a main driver are proposed in [Deneire00a, Deneire00b] and importance and implications of power and QoS awareness are addressed in [Eberle02e].

Chapter 4 presents the complete functional and architectural concept for the digital signal processing core of the OFDM wireless LAN modem. The data rate extension to about 100 Mbit s\(^{-1}\) required innovations in algorithmic and architectural design. Moreover, an innovative C++-based design flow was applied. Each design step is motivated and placed in the context of this design flow. Finally, observations from the two ASIC designs and an FPGA implementation are analyzed:
We proved that a cost-efficient solution for the core-FFT functionality is viable and that the FFT is not the design bottleneck for OFDM wireless LAN [Eberle97b, Eberle99a, Vergara98a, Gyselinckx99].

A functional low-cost transceiver concept for OFDM was introduced in [Eberle99a, Eberle01b]; a high-performance transceiver concept was added in [Eberle01a]. Importantly, both concepts distinguished themselves from the state of the art by a significant increase in data rate and the integration of the complete synchronization and equalization functionality of the receiver. Particular aspects on acquisition and synchronization were further published in [Eberle00c, Fort03a].

Both low-cost and high-performance transceivers were implemented and experimentally verified as ASICs in digital 0.35- and 0.18-µm CMOS technology using a novel C++ design flow [Eberle00a, Eberle01a, Eberle01b]. The chosen distributed multiprocessor architecture has an excellent scalability. Details and an extension to a digital-IF front-end were published in [Eberle98b, Eberle00b].

A patent on the transceiver architecture was filed in 1999 and has been granted in 2004. It covers in particular the partial reuse, data format conversion, and acquisition architecture [Eberle99b].

Chapter 5 extends the work in the previous chapter toward the analog receiver front-end. This widening in focus is crucial since analog nonidealities have proven to have a more detrimental effect than the already harsh indoor radio channel. In particular, we address predominantly digital and hence scalable techniques to mitigate gain, offset, mismatch, and phase noise problems. These improvements can be used either to relax front-end specifications, and hence cost, or to increase performance at equal cost. Specific attention in algorithmic and architectural development was required since the wireless LAN packet transmission scheme requires estimation and compensation of these nonidealities being accomplished at low protocol overhead. We will show that this combination of requirements renders most existing solutions unusable:

Front-end compensation techniques have been published in [Eberle00c, Eberle02a, Eberle02b, Eberle02c, Eberle03] for automatic gain control and DC offset compensation; in [Fort03b], an approach for efficient interaction between automatic gain control and synchronization is described. Our AGC approach has also been described as a concrete application case for design-time/run-time multiobjective optimization in a patent filing [Eberle02d].

The impact of the transmit/receive transfer function, including radio channel, analog, and digital filtering, on timing synchronization has been studied in [Debaillie01a, Debaillie01b, Debaillie02], leading to practical design criteria for filters and timing synchronization.
In [Eberle02a, Côme04], we proposed an elegant architectural extension to the OFDM core that embeds all compensation techniques; the result is a practically relevant and consistent acquisition and tracking architecture.

Chapter 6 raises the abstraction level from subsystem to system design, particularly to the design of the radio link. Application scenarios for wireless LANs are very variable with changing environments, variable payload traffic, and QoS requirements. Traditionally, systems were statically designed to cope with the worst-case link and traffic conditions, with unrealistically high-power consumption as a result. Consequently, the power amplifier was identified as the main power bottleneck. We show how design-time scenario exploration can lead to better component choices and how run-time QoS-driven component usage can significantly reduce the average power consumption:

- QoS-driven multiobjective system exploration and scenario-/application-aware design are described in [Eberle02e, VanDriessche03] with main focus on the transmitter; an extension including receiver scalability appears in [Bougard03a].
- Practicality of transmit chain power reduction has been studied for the power amplifier in [Eberle02c, VanDriessche03, Bougard03a]; compatible digital signal adaptation methods in the transmitter have also been studied.
- The design-time/run-time approach for a QoS link between analog component steering knobs and higher-layer QoS decisions is described for the power amplifier case in a patent filing [Eberle02d].

Chapter 7 presents the design flow and design methodology developed and applied in Chaps. 4–6. While particular methodology aspects have been introduced already there, this chapter falls in two parts: first, we describe design technology developed to efficiently implement methodology; second, we situate these techniques in an integrated flow for mixed-signal transceiver design. This flow extends the traditional focus of detailed design refinement to two threatening methodology gaps in efficient design space exploration and crosslayer design.

- The application and extension of C++-based design technology for digital ASIC design from the architectural to the synthesis-entry level are described in [Eberle98a, Eberle01b, Verkest01a].
- A digital reuse case involving two ASICs and one FPGA designs is analyzed; some observations have been published in [Verkest01a, Eberle01b].
- The development of MATLAB/C++-based simulation technology for front-end and mixed-signal design and its integration with the digital design flow is detailed in [Vandersteen01, Wambacq01, Wambacq02a, Wambacq02b]; particular behavioral modeling techniques for strong
mixed-signal interaction are addressed in [Eberle03].

- Our design-time/run-time approach for mixed-signal systems is described in [Eberle02d] and illustrated in [VanDriessche03, Bougard03a].

Chapter 8 concludes with a review of the major achievements and a comparison of the actual design results to the objectives. Forthcoming from our research, a selection of promising topics for future research is presented.
2 The System Design Process

Everyone takes the limits of his own vision for the limits of the world.
Arthur Schopenhauer, 1788–1860.\textsuperscript{15}

Research in microelectronic integration for wireless LANs is obviously the right way to go to obtain low-cost low-power solutions that meet business expectations for a consumer market. So, why not start designing them ad hoc, right now?

Maybe because a few questions remain, such as do we have a clear specification of what we want to obtain as a result? Do we know how we get from our expectations toward a prototype implementation or a final product? Can we repeat this process?\textsuperscript{16} And finally, what does design actually mean?

Designing\textsuperscript{17} as a human activity is not easily captured in a single definition, but a combination of creating or executing in a highly skilled manner, formulating a plan or devise something, and having something as goal or purpose [AHD00] seems to bring together all important aspects: each design needs a clear goal to achieve; it requires the concept of a method, path, or process that leads to this goal; and it relies on particular skills to reach the goal while staying on the intended path.

\textsuperscript{15} Schopenhauer’s words – “Jeder Mensch hält die Grenzen der Wahrnehmung für die Grenzen der Welt.” – obviously go beyond simple perceptions of working style; but has not there always been a fight between old and new methods of accomplishing things? Schopenhauer mentions also that this often includes that new thoughts are first ridiculed, then attacked, and finally become common thinking – “Ein neuer Gedanke wird zuerst verlacht, dann bekämpft, bis er nach längerer Zeit als selbstverständlich gilt.”

\textsuperscript{16} Obviously, products are designed everyday. A fundamental question is how much experience from previous designs plays a role to reproduce a design success and whether and how some of this experience can be transferred from an experienced human designer to other designers, into a methodology, or into tools.

\textsuperscript{17} The word design has its origin in the Latin word designare which means to devise (to invent), to mark out for something.
A particular design activity relies on a requirements specification as input on what to achieve and is basically given freedom in how to achieve it. Obviously, the most efficient process of achieving the specification is desired. Traditionally, requirements for an electronic system could be rather easily and early partitioned into a few discrete disciplines such as analog and digital, mechanical and electronic, low-power and high-power parts, etc. Little margins on cost, power consumption, and performance for portable, consumer-oriented devices such as WLAN do not allow such an upfront partitioning; instead, a multiobjective system-level optimization is preferred. The definition of a system directly explains that codesign and optimization at a larger scope, taking into account more components together, offer a potential benefit in better functionality or lower cost. However, it also complicates the design process since the design space has been enlarged. Fig. 2.1 illustrates the difference between vertical intratechnology and horizontal intertechnology exploration. The figure is an extension of Kienhuis’ abstraction pyramid [Kienhuis99].

If we assume that the same design cost can be spent, then we might reduce design cost along the vertical design space exploration axis and shift it to the horizontal exploration axis. First, this requires increased efficiency in design refinement and synthesis within a particular technology or discipline. During the last years, progress has been made on this aspect. Second, horizontal exploration requires understanding and interaction between traditionally different skills, hence interdisciplinarity. Kienhuis [Kienhuis99] stated that an increase in abstraction level leads to lower exploration cost. However, he assumed the availability of efficient and sufficiently accurate behavioral models. This assumption neither does hold for analog and microwave/RF nor will be applicable for digital designs processed in nanotechnology. Also, intertechnology exploration leads to heterogeneous modeling approaches, which largely increase the complexity of horizontal design space exploration. Colwell [Colwell04] stated this as “there’s always cost in tying conceptually separate functions together.” But, is there an alternative and are these functions actually conceptually separate?

This chapter is organized as follows. Section 2.1 describes design as a process. We introduce terminology and the scope of design methodologies and design technology. Section 2.2 focuses on microelectronic system design. Requirements and common approaches are described that allow the identification of areas of mature design technology and methodology gaps. Finally, we synthesize our particular design approach for WLAN. Section 2.3 analyzes the consequences of such a design flow based on different levels of crossdisciplinarity. Codesign of design technology and application is addressed in particular. Section 2.4

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18 A system can be defined as a set of interrelated elements perceived as a whole, performing a useful function by interaction with human or other environment. A system is composed of components, typically in a hierarchical way. The interrelation makes the system more useful than the sum of its isolated components. The system reacts to or interacts with its environment.
summarizes our findings and directs the reader to the implications of our design rationale in Chaps. 4–7.

Fig. 2.1. Extension of the abstraction pyramid to a multisegmented abstraction circle which captures both intratechnology (vertical) and intertechnology (horizontal) exploration. Horizontal exploration within one technology may start a trajectory of changes across multiple technologies to meet overall specifications.

2.1 Design

Both artists and engineers rely on creativity, rooted in knowledge, and craftsmanship, as means for innovation. In principal, they both start with a blank page and a few requirements. However, in contrast to the fine arts, design in the engineering context has become far more constrained a priori by nontechnical requirements and cost aspects [Rissone02]. The amount of constraints allows a distinction between two different design goals: the design of a new product and the design of a derivative of an existing product. The first refers to the blank page