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by

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A mamma, papà, Carmelo e Luca perché so di poter sempre contare su di loro.

To Beatriz and our sweetest baby girl, Sofia Melina, for their love, trust and constant support.

Preface

WITH the rapid development of wireless communication networks, it is expected that fourth-generation (4G) mobile systems will appear in the market by the end of this decade. These systems will aim at seamlessly integrating the existing wireless technologies on a single handset: together with the traditional power/size/price limitations, the mobile terminal should now comply with a multitude of wireless standards. Software Defined Radio (SDR) can be the right answer to this technology demand. By restricting the meaning of the term SDR to the analog world, we refer to a transceiver whose key performances are defined by software and which supports multistandard reception by tuning to any carrier frequency and by selecting any channel bandwidth (Abidi, 2006). In the future, SDR might become a "full digital" Software Radio (SR) (Mitola, 1995, 1999) where the digitization is close to the antenna and most of the processing is performed by a high-speed Digital Signal Processor (DSP). Though, at present, the original SR idea is far ahead of state of the art, mainly because it would demand unrealistic performance for the Analog to Digital Converter (ADC).

We believe that a fully reconfigurable Zero-IF architecture that exploits extensive migration toward digitally assisted analog blocks (Craninckx et al., 2007) is the best candidate to realize a SDR front end as it has the highest potential to reduce costs, size, and power, even under flexibility constraints. Although this solution itself does not allow simultaneous reception of more than one channel, two parallel front ends of this kind would cover most of the user needs, while still allowing cost saving compared to parallel single-mode radios.

The objective of this book is to describe the transition towards a SDR from the analog design perspective. Most of the existent front-end architectures are explored from the flexibility point of view. A complete overview of the actual state of the art for reconfigurable transceivers is given in detail, focusing on the challenges imposed by flexibility in analog design. As far as the design of adaptive analog circuits is concerned, specifications like bandwidth, gain, noise, resolution, and linearity should be programmable. The development of circuit topologies and architectures that can be easily reconfigured while providing a near optimal power/performance trade-off is a key challenge. The goal of this book is to provide flexibility solutions for analog circuits that allow baseband analog circuits to be part of an SDR front end architecture. In more detail, there are two main features that need to be implemented:

- **Performance reconfigurability.** This allows compatibility with a wide range of wireless standards. In analog words, that means that parameters such as cut-off frequency, selectivity, noise, and linearity for the filter, gain, and bandwidth for the amplifier, number of bits, and sampling frequency for the ADC, should be digitally programmable.

- **Energy scalability.** Let us assume that the task is to transmit a packet of L bytes. Suppose that the considered system can proceed to that transmission at a rate R byte/s with a power PW or at rate $(R/2)$ byte/s with power $(2P/3)$ W. This is hence a power manageable component since a lower performance leads to a lower energy per bit (Bougard, 2006).

The challenge is then to provide at any time the best power consumption vs performance trade-off. It is clear that analog reconfigurability may come at the cost of power, silicon area, and complexity. Therefore, one of the goals is to try to minimize such costs. We will have to deal with many cross-disciplinary aspects which are the key to a good-enough analog design with reduced die size, power consumption, and time-to-market. They will be emphasized at all design steps, from defining requirements at first, to deriving specifications through end-to-end system simulation, and finally global verifications.

The book is structured as follows:

- **Chapter 1** discusses the benefits and the enormous challenges of migrating to fourth generation (4G) mobile systems focusing on the mobile handset. The role of analog circuits is identified and a possible platform for the mobile terminal is proposed.

- **Chapter 2** investigates a number of architectural issues and trade-offs involved in the design of analog transceivers for a fully integrated multi-standard SDR. After commenting on the state of the art for SDR front end integrated circuits, a flexible zero-IF architecture for SDR is suggested, supported by implementation and measurements results.

- **Chapter 3** discusses the practical aspects that have to be taken into account when the specifications for an SDR must be derived. The optimal specifications distribution for minimum power consumption is given focusing on the baseband section.

- **Chapter 4** comments on the challenges that analog design for flexibility imposes to a designer and shows a possible way to tackle them. Basic flexible analog building blocks are then analyzed from the flexibility perspective trying to figure out an optimal implementation.

- **Chapter 5** shows two possible implementations of flexible baseband analog sections. The implementations are described and measurements results prove the validity of the proposed approaches.

Finally, this book is the result of a Ph.D. research work and, as such, it comes out of years of readings, study, and hard work. We do realize that it could be definitely improved as errors or omissions may easily occur in works of this kind. Many of the analog techniques described in the book have already been published in the past and references are carefully reported so that the reader can eventually further delve into the topic. We would strongly appreciate if you could bring your opinion to our attention so that eventual future editions can be improved.

VITO GIANNINI

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WE express our sincere gratitude to all those who gave their contribution to make this book possible both at IMEC and University of Salento. In particular, we deeply appreciate the work of our colleagues whose active contribution improved the contents of this book. Stefano D'Amico deserves a special mention as he is the inventor of the Active-G_m-RC cell, which is extensively described in Chapters 4 and 5. Bjorn Debaille dealt with the compensation techniques of analog imperfections and the Automatic Gain Control loop, discussed respectively in Chapters 2 and 3. We thank Joris Van Driessche, who provided most of the system-level results, discussed in Chapter 3. Bruno Bougard provided all the necessary information to briefly describe the flexible air interface. A special thanks goes to all the members of the Wireless Group at IMEC whose hard work, in different ways, helped in achieving the implementation of a full Software Defined Radio transceiver, which is partly described in Chapter 2, and for contributing to a research environment that has proven to be immensely rewarding. We thank Pierlugi Nuzzo, Mark Ingels, Charlotte Soens, and Julien Ryckaert for the enlightening technical discussions. We also thank Boris Come, Filip Louagie, and Liesbet Van Der Perre for the constant trust, confidence, and support.

30 May 2007
Leuven, Belgium

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Chapter 1

4G MOBILE TERMINALS

WITH the rapid development of wireless communication networks, it is expected that 4G mobile systems will be sent to market by the end of this decade. While third-generation (3G) mobile systems focused on developing new standards and hardware, their 4G evolution will aim at seamlessly integrating the existing wireless technologies (Hui and Yeung, 2003). Fourth-generation systems will support comprehensive and personalized services, providing not only high-quality multimedia and broadband connectivity, but also high usability (wireless connection anytime and anywhere). However, migrating current systems to 4G presents enormous challenges and, in particular, the design of the mobile terminal represents the real bottleneck because of the concurrent power/performance/price limitations that a base station does not have (De Man, 2005). This chapter will discuss these challenges.

1.1 A Wireless-Centric World

Since Nikola Tesla, in 1893, carried his first experiments with high-frequency electric currents and publicly demonstrated the principles of radio broadcasting, society witnessed so many changes in which that discovery had an important role. Wireless communication has become incredibly essential in today's world. Whether we will want it or not, wireless devices will have, increasingly, a significant impact in our everyday life.

In the close future, a smart wireless device able to provide information, communication, and entertainment could be in the pockets of millions of users. This Universal Personal Assistant (UPA) will be powered by battery or fuel cell (De Man, 2005). In the business environment, it would serve the purpose of mobile computing, wideband ubiquitous communication, and audio/video conferencing. High-speed data links will be provided by Wireless Local Area

Network (WLAN), but only in the home of office environments and at a number of hot spots, e.g. in airports. Global coverage for connection to the rest of the world happens over the radio access link of a cellular or satellite network. For example, in our cars, it would lead to security improvements and intelligent navigation. The entertainment industry could propose new advanced gaming services usable anywhere. The mobile terminal could become a real-time health wireless monitor, where body temperature, heart rate, and blood pressure could be checked anytime for high-risk individuals still allowing them to live a normal life. A high level on encryption and new advances in cryptography might enable the use of electronic cash by simply pushing a button on a mobile handset, which could also allow access to its owners to create wireless keys for homes, cars, and safes. Finally, governments could allow the use of wireless identification devices. All this culminates in the vision of Ambient Intelligence (AmI), a vision of a world in which the environment is sensitive, adaptive, and responsive to the presence of people and objects (Boekhorst, 2002) and the user is able to interact at several levels with several objects.

Typically, this AmI vision involves discussions at very different levels: from more technical details to ethics and privacy issues. Focusing on the technology challenges, what is clear is that to enable this vision two things will be essential:

- A Wireless Sensors Network (WSN)
- A Smart Reconfigurable Wireless Terminal

While several universities and research centers are actively working on WSN, the idea to develop a smart wireless terminal is already at more advanced stages forced by the strong demand for highly flexible transceivers. The proliferation of mobile standards and the mobile networks evolution make the global roaming and multiple standard compliancy a must for a modern terminal. The problem of integrating more radios on a single terminal involves discussions on performance, that has to be good enough to receive different modulations, carrier frequencies, and bandwidths. Power consumption is critical for such devices, where the need of tougher performance contrasts with the always actual problem of extending the battery life as long as possible. In addition to that, the number of components on a single terminal might have an impact on the size/cost of the final wireless product. In this context, the possibility to reduce the number of components on a single mobile terminal by integrating different radios on a single radio Integrated Circuit (IC) could indeed allow cost savings while still guaranteeing optimal power/perfomance/cost trade-offs.

If we wanted to put the vision previously described in terms of wireless standard needed for a certain application, we would realize how it is actually very difficult to have a single terminal able to work for such a wide range of services. While voice digital broadcasting requires high mobility at low data rates, a video phone call needs devices compliant with data rates as high as

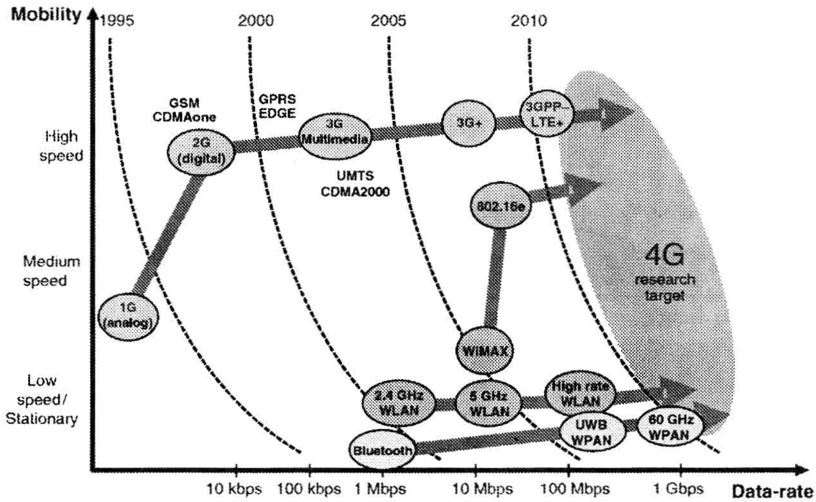

Figure 1.1. Plethora of emerging and legacy wireless standards.

100 Mb/s. Finally, low data rate control signals that form the interface between environment and system with data rates as low as 100 Kb/s (i.e. a wireless health monitor) might require a Wireless Personal Area Network (WPAN), and so low mobility, wide band, and even tougher power constraints. Figure 1.1 shows a compact picture of the evolution of the wireless standard versus the mobility/data rates requirements.

Energy-efficient platforms are needed that can be adapted to new standards and applications, preferably by loading new embedded system software, or by fast incremental modifications to obtain derived products. This might be possible by exploiting the intrinsic capabilities offered by CMOS deep submicron processes.

1.2 The Driving Forces Towards 4G Systems

Since mobile phones began to proliferate in the early 1980s with the introduction of cellular networks many steps have been done. The success of second-generation (2G) systems such as GSM and CDMA in the 1990s prompted the development of their wider bandwidth evolution. While 2G systems were designed to carry speech and low-bit-rate data, 3G systems were designed to provide higher-data-rate services. Figure 1.2 shows this technology evolution: a range of wireless systems, including GPRS, EDGE, Bluetooth, and WLAN, have been developed in the last years that provide different kind of services. All these systems were designed independently, targeting different service types, data rates, and users. As these systems all have their own merits and shortcomings, there is no single system that is good enough to replace all the other

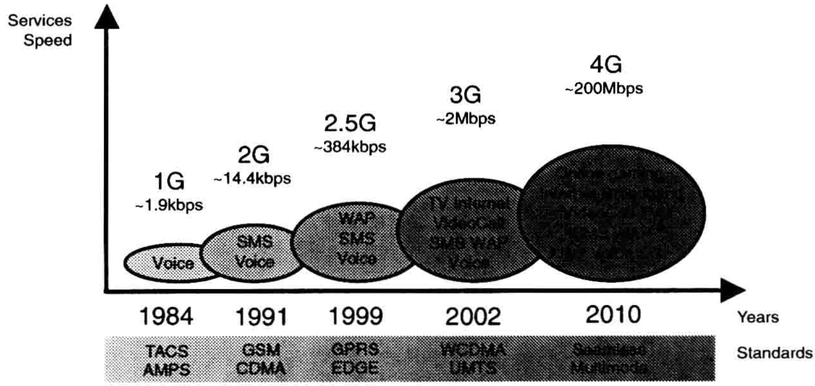

Figure 1.2. Short history of mobile telephone technologies.

technologies. Driven by the enormous success of the Internet over the last 10 years, with steadily increasing data rates and deployment of new services, extra expectations have emerged. Not only traveling businessmen and executives, who were already the early adopters of cellular communications, but the wide majority of mobile users demand for low-cost connectivity while on the move (Zanariadis, 2004). Instead of putting efforts into developing new radio interfaces and technologies for 4G systems, we believe establishing 4G systems that integrate existing and newly developed wireless systems is a more feasible option.

The following requirements for a 4G terminal are identified as important drivers for the research on the mobile terminal:

- **High usability.** 4G networks are all-IP based heterogeneous networks that allow users to use any service at any time and anywhere. Low-cost ubiquitous presence of all broadcast services, with bit rates comparable to those offered by wired systems, forms a compelling package for the end user and can truly make the mobile terminal a centrepiece of people's lives. Ubiquitous coverage is a key feature to have an impact on the market because users might not be willing to renounce to the fine coverage of the Global System for Mobile Communication (GSM) services in favor of more advanced but poorly available (at least in the early stages of development) wireless networks. Therefore, it is essential to develop an architecture that is scalable and can cover large geographical areas and adapt to various radio environments with highly scalable bit rates, while encompassing the personal space (BAN/PAN) for virtual reality at faraway places.

- **High-quality multimedia.** *Video conferencing* is an essential part of the mobile terminal. Having an autonomy for at least 1 h, of full high-quality video conferencing with four participants is strategic for the proliferation