Doctoral Thesis

Reconfigurable Integrated Circuits

summary

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Introduction

Given the rapid and complex development of the modern wireless networks in the last years, a significant number of relevant research shows that the terminals and network equipment need to possess a high degree of intelligence in order to adapt to the users’ mobility and quality of services requirements. The large number of existing standards as well as the large number of communications standards that are envisaged to appear in the future create the need to reconfigure and adapt all the components of a wireless network to user requirements.

The most important aspect that motivates the study of the problem of reconfigurability in wireless communications systems refers to the need to offer to users complete access through a single mobile device to all the communications standards existing today as well as to those to come. It follows that all the wireless services may be marketed using only one mobile terminal that possesses a high degree of flexibility in what concerns the radio access technique and software and hardware-adaptable to the specifications of all envisages standards.

The objective of implementing a mobile terminal compatible with virtually any wireless standard I studied in the context of the Software Defined Radio (SDR) technology that refers, in its widest acceptance, to the unrestricted programability of all the services and functions in a mobile communications system, from the physical specifications of the electronic circuits up to the protocols and interfaces of software applications.

Due to the digital techniques of signal processing, the most important characteristic of an SDR terminal is represented by the possibility of adapting the signal processing operations to the specifications of any wireless standard. It results, therefore, a mobile terminal that, ideally, is capable of operating in any frequency band and is able to demodulate any signal whose specifications are described in software.

The main objectives of the doctoral thesis are derived directly from these general considerations:

- the study (analysis) of reconfigurability methods for analog integrated circuits
- the implementation (synthesis) of analog reconfigurable circuits
- the development of a significative contribution towards the implementation of a functional SDR terminal

The doctoral thesis is structured in five chapters. The first chapter, the introduction, presents the motivation and the content of the thesis. In the second chapter “Fundamental concepts in the context of the SDR technology” I present the fundamental notions that allow the positioning of the thematic within the current modern research trend of the SDR technology. The third chapter, “Notes on the analog reconfigurable filters with transconductors” deals with the study of the analog programmable and reconfigurable filters synthesized either with biquads or with state variables. As a conclusion of the research done in the previous chapters, in the fourth chapter I present two versions, the initial and the improved one, of a proposed reconfigurable and programmable analog array. Both structures aim at verifying the correct operation of the analog reconfigurable and programmable filter design for the
transceiver architecture proposed in the second chapter. In this chapter I include the simulation results performed on the two versions of the analog array for real low pass filters and complex band pass filters that allow a digital control of their order, approximation, cut-off frequency and bandwidth. All the circuits are SPICE simulated and included in a modular library developed by the author. In the fifth and last chapter I underline the main personal contributions in the achievement of the objectives, as well as future possible research of the thematic.

1. Fundamental concepts in the context of the SDR technology

The SDR technology refers, in its widest acceptance, at the unrestricted programmability, functions and services from a mobile communications system, from the physical characteristics of the circuits and radio interfaces to the software applications. In what concerns the mobile terminals, the SDR technology allows the implementation of a radio transceiver in which the key parameters that describe the way the radio modem works are defined in software and in which their parameters can be changed by updating this software. The main characteristic of an SDR terminal is given by the signal processing performed in flexible analog and digital hardware units, programmable and reconfigurable. Unlike the latest implementations of mobile terminals, an SDR transceiver’s main feature is that its functionality is dictated by software and not by hardware. A large extent of an SDR functions are implemented through algorithms that are capable to control the hardware components using digital programming streams of bits. The design itself of such a radio concentrates around the design of efficient algorithms and not deals with the design of hardware-specific blocks that are dedicated to each signal processing unit. The emerge of the software radio concept determined the crystallization of an entire theory of reconfigurable radios. It is in this context of adaptive and evolutive circuits that the new concepts such as Software Based Radio and Software Radio emerged, as stages in the evolution of the most advanced mobile terminals. In what follows I propose a number of definitions that aim at ordering the research space concerning the reconfigurability for software defined mobile terminals:

1\textsuperscript{st} Definition
A Software Based Radio (SBR) is that radio devices that uses software techniques to process the received radio signal.

2\textsuperscript{nd} Definition
A Software Defined Radio is that radio device in which the functionality of the entire system is determined by algorithms that control the hardware platform in which the analog and digital reconfigurable and programmable components process the radiofrequency received signals.

3\textsuperscript{rd} Definition
A Software Radio is that radio in which the received radiofrequency signal is digitized as close as possible to the antenna in order to allow the implementation of the radio functions in the digital domain through software (Figure 1).
Specifications of a software defined radio

The chain of signal processing operations from a wireless receiver can be seen as a sequence of mathematical operators that are applied to the income received signal. It follows that the number of these operations must be minimized to one stage of frequency conversion and a minimum number of filters and amplifiers. At the same time, a reconfigurable receiver must allow a digital control of the parameters that implement the reconfiguration strategy.

These considerations determine the most important two specifications of a software defined radio:
- Flexibility, obtained through programmability and reconfigurability, and
- interoperability.

4. Dedicated analog array for the implementation of programmable and reconfigurable analog filters with transconductors
The system architecture of the analog array that implements the programmable and reconfigurable filtering unit is presented in Figure 8. The system comprises of:

- a digital bus,
- an analog bus,
- a programmability and reconfigurability management unit, with associated decoding logic and buffers,
- a performance monitoring unit and
- a central array of programmable transconductor cells (8x6 gm cells).

![System architecture of the analog array](image)

**Enhanced version of the analog array**

The architecture of the analog array presented above was changed in order to minimize the number of switches in the array and particularly those placed on signal paths. The 48 reconfigurable and programmable analog cells were replaced by a structure made of 8x3 analog reconfigurable and programmable analog units (UARP) interconnected by specific connection circuits.
Each reconfigurable and programmable analog unit from Figure 4 contains two transconductor cells that are recurrently interconnected in a feedback connection. Each UARP structure benefits from a single differential input/output, hence allowing the overall analog array to feature no more than three input and output signals at the same time.

Performance evaluation of the filters implemented with the two analog arrays

In what follows I present two examples that illustrate the correctness operation of the analog array in both versions. For the low pass filters I choose the Chebyshev approximations with a 0.5 dB ripple, and Butterworth. The filters of orders 4 and 6 are Butterworth approximated, while the ones of odd order (5 and 7) are Chebyshev approximated. All filters have a cut-off frequency of 10 MHz. The flexibility of the analog array is demonstrated not only by the possibility of adapting the circuit structures to the specifications of filters of diverse orders and approximations, but also by the possibility to implement several such filters concomitantly on the analog array. In what concerns the complex band pass filters of
orders 4, 5, 6 and 7 I used the Chebyshev approximation with ripple of 0.5 dB. Staring from the passive low pass prototypes with a cut off of 2 MHz, all four complex filters have a bandwidth of 4 MHz and a central frequency of 10 MHz.

The low pass filters are designed to filter wide band signals received by the SDR receiver, such as CDMA signals, while the complex band pass filters are envisaged to filter narrow band signals, such as GSM.

Figure 5 shows the correct operation of the analog array, as the transfer functions implemented by the passive prototype of order four ($V(\text{out}_\text{passiv}4)$), the transfer function of the differential circuit ($V(\text{out}_\text{diferential}4)$) and the transfer function of the analog array ($V(\text{out}_\text{array}4)$) are all identical.

![Figure 5 The amplitude and phase transfer functions of the 4th order Butterworth filter](image)

The implemented complex filters are directly derived from the low pass prototypes with a pass band of 2 MHz. Simulating these filters and comparing them with the differential dedicated-circuit implementation with transconductors yields identical results, demonstrating the correct operation of the analog array (Figure 6).
Figure 6 Phase and amplitude transfer functions of a 4th order Chebyshev complex band pass filter, $0.5\, \text{dB}, f_c=10\, \text{MHz}, \text{BW}=4\, \text{MHz}$

5. Conclusions

The original contributions of the doctoral thesis are summarized in what follows:

- I proposed the definition of two new concept: SBR and SR
- I performed a statistical study on the most discussed transceiver architectures in the current flow of published research
- I proposed the combined low-IF/zero-IF as the best candidate architecture for the implementation of the SDR receivers
- I simulated using SPICE two architectures of analog array that are suited for the implementation of the filter stage in an SDR terminal
- I demonstrated the feasibility of implementation for reconfigurable and programmable analog filters