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Software Defined Electronics: A Revolutionary Change in Design and Teaching Paradigm of RF Radio Communications Systems

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Abstract

Band-pass signals are used everywhere in radio communications. The band-pass property makes the substitution of each RF/microwave/optical analog signal processing possible with a low-frequency digital one in Software Defined Electronics (SDE). In SDE, the high frequency band-pass signals are transformed into the BaseBand (BB) by a universal HW device and every application is implemented in BB, entirely in software. SDE concept uses (i) the lowest sampling rate attainable theoretically and (ii) the same universal HW device in every application. The huge level of flexibility offered by the SW implementation is essential in many applications from cognitive radio to adaptive reconfigurable systems. This tutorial, written for interested readers who have no solid background in software defined radio, virtual instrumentation and SoC technology, surveys the SDE theory, uses a step-by-step approach for the derivation of BB equivalents and demonstrates the application of SDE concept in scientific research, prototyping and education.

Index Terms: Software defined electronics, equivalent baseband implementation, software defined radio, virtual instru-mentation

I. Introduction

The general trend of our days is that the HW and SW components are becoming completely separated, the different applications are implemented entirely in SW, and only one universal HW device is used to establish the connection between the data streams processed and generated in SW and the physical signals mea-sured in the real world. The most important feature of SW implementation is that both the functionality and parameters of each application can be changed easily in SW. This flexibility is essential in many applications from cognitive radio to adaptive systems. For exam-ple, if the cognitive radio transceiver is implemented according to the Software Defined Electronics (SDE) concept then the same HW platform can be used to evaluate the channel conditions and implement the radio transceiver just by changing the SW.

The three main constituting elements of SDE concept such as the theory of complex envelope [1], Software Defined Radio (SDR) [2]-[3], Virtual Instrumentation (VI) [4] have been available for a long time. However,(i) universal HW devices capable of operating in the RF, microwave and optical frequency regions have been available only recently at a reasonable price and (ii) a unified and integrated theory for the software defined approach has not been available up to now.

The SDE concept offers this framework by inte-grating the already known solutions into one unified theory and by providing a SW-based platform for the design, development, implementation and teaching of telecommunications and measurement systems.

The use of SDR and VI technologies either in educa-tion or in scientific research has required a lot of special knowledge in many areas from microwave/optical engineering to FPGA programming before the advent of SDE concept. The lack of this special knowledge and access to IC technology prevented the use of software defined concept in many cases. The SDE concept offers a solution to this problem because

- it integrates many technologies into one unified and simple framework;
- it provides a BaseBand (BB) interface, con-sequently, everybody who has a SW simula-tor in BB can turn that SW directly into an real physical systems without building any mi-crowave/optical circuits or learning FPGA pro-gramming.

This tutorial provides a self-contained, comprehensive survey of the SDE concept. However, it does not aim readers who have a solid background and a lot of expertise in SDR, VI and SoC technologies, or in

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FPGA programming. Instead, it provides an easy-to-use tool for those who are working on signal processing, telecommunication engineering and test systems, and who want to implement their system or verify their research results without spending a lot of time and money on the implementation issues.

The paper is organized as follows. Section 2 surveys the theory of complex envelopes that gives the mathematical background of the SDE concept.

Every application is implemented in BB in the SDE concept and a linear transformation is used to establish the relationship between the real world, i.e., the RF band-pass signals and systems, and their low-pass BB equivalents. Section 3 discusses all aspects of SDE concept from the basic concept to the derivation and cascading of BB equivalents.

In research and prototyping the new results are verified first by computer simulation. Section 4 shows how a MATLAB BB simulator can be turned into a real working radio system if it is integrated into the SDE platform. Both the operation principle and the block diagram of a PXI-based universal SDE platform are discussed. Its main features are: (i) any kind of BB simulators can be integrated directly into the universal SDE platform and (ii) it can implement any telecommunications and measurement systems without building any HW components.

Telecommunications and test systems of our times are becoming more and more complex. The main challenge is not in the circuit design but in the integration of many different HW and SW platforms into one application. The next generation of engineers has to be able to cope with this challenge, consequently, the teaching paradigm of RF radio communications and test systems has to be changed. Section 5 is devoted to this issue.

2 MATHEMATICAL BACKGROUND: BASEBAND EQUIVALENTS

Band-pass signals are used in radio communications to convey information from transmitter to receiver. To implement an application *entirely in software*, all analog signals must be digitized. The most crucial issue is the assurance of minimum sampling rate without corrupting the information carried by the RF bandpass signal. The lowest sampling rate attainable theoretically is obtained by using the *equivalent baseband transformation*.

2.1 Complex Envelopes

To get the definition of *complex envelope* consider a RF real-valued *band-pass* signal $x(t)$. Assume that the spectrum $X(f)$ of $x(t)$ is zero or negligible out of the RF bandwidth $2B$ centered about the center frequency f_c as shown in Fig. 1(a). In case of a modulated signal f_c is referred to as carrier frequency.

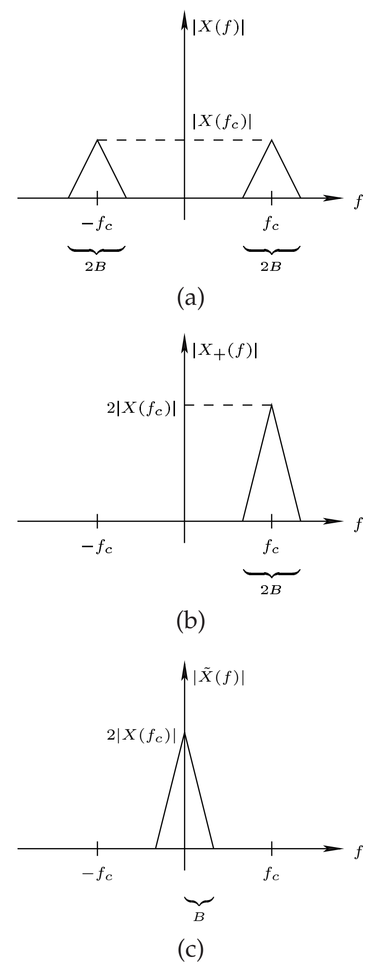

Figure 1. Derivation of complex envelope: spectra of (a) the original RF band-pass signal, (b) its pre-envelope and (c) its complex envelope.

In equivalent BB signal processing the RF band-pass signal is decomposed into the product of a complex envelope $\tilde{x}(t)$ and the carrier $\exp(j\omega_c t)$

$$x(t) = \Re\left[\tilde{x}(t)\ \exp(j\omega_c t)\right]$$

where the real and imaginary parts of slowly-varying complex envelope

$$\tilde{x}(t) = x_I(t) + jx_Q(t) \qquad (1)$$

are referred to as the I and Q components, respectively.

The derivation of complex envelope can be followed in the frequency domain. The spectra of RF band-pass signal $x(t)$ to be transformed into BB is plotted in Fig. 1(a). The goal is to transform this spectrum into BB as shown in Fig. 1(c).