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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.

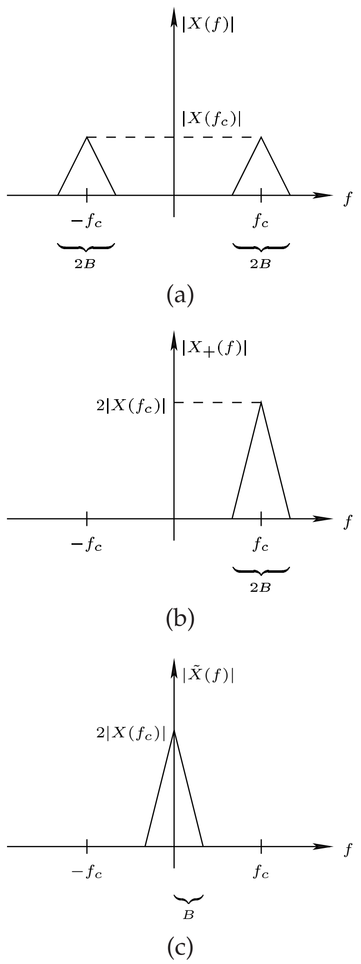


Figure 1. Derivation of complex envelope: spectra of (a) the original RF band-pass signal, (b) its pre-envelope and (c) its complex envelope.

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

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

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).

Unfortunately, each real-valued signal has a two-sided spectrum that cannot be shifted directly to BB. An intermediate step is required where a one-sided spectrum is formed.

The pre-envelope of the RF bandpass signal $x(t)$ is defined by

$$x_+(t) = x(t) + j\hat{x}(t)$$

where $\hat{x}(t)$ denotes the Hilbert transform [1] of $x(t)$. As shown in Fig. 1(b), the pre-envelope has a one-sided spectrum, consequently, it can be shifted to BB in order to get the complex envelope depicted in Fig. 1(c). Note, except the derivation of complex envelope, the pre-envelope is not used in the SDE concept.

The complex envelope $\tilde{x}(t)$ of Fig. 1(c) is a low-pass signal. Except the center frequency f_c, $\tilde{x}(t)$ carries all information available in the original RF bandpass signal $x(t)$, consequently, signal processing to be performed in the RF bandpass domain can be fully substituted by an equivalent BB one. Equation (1) shows the only price that has to be paid, not real- but *complex-valued* signals have to be processed in equivalent BB implementation.

Comparison of Figs. 1(a) and (c) shows the two crucial features of equivalent BB signal processing:

- sampling rate required to process the information carried by the RF band-pass signal $x(t)$ is reduced from $2(f_c + B)$ to $2B$ in equivalent BB signal processing;
- because the information is carried in the frequency band where the spectrum $X(f)$ of RF band-pass signal differs from zero or is not negligible, the equivalent BB signal processing assures the lowest sampling rate attainable theoretically.

2.2 Properties of BB Signal Processing

Modeling and implementation of each telecommunications system including radio channel need to consider three constituting components:

- deterministic signals discussed in Sec. 2.1;
- Linear Time Invariant (LTI) blocks;
- random processes.

As shown in [1], [3], [5]-[6], BB equivalents can be derived for each constituting component of a radio link. The most important characteristics of BB equivalents are:

- BB equivalents of each *RF band-pass* deterministic signal, LTI block and random process have a *low-pass* property where the sampling rate required in BB is determined by the half of bandwidth measured in the RF band-pass domain;
- RF band-pass signal processing can be fully substituted by an equivalent BB one;
- except the center frequency f_c, the BB equivalent retains all information available in the RF band-pass domain;
- it is a *representation* and not an approximation, consequently, distortion does not occur.

The relationship between the RF band-pass and BB low-pass domains is established by a linear transformation. The block diagrams of transformation in both direction and more details on the theory of complex envelopes can be found in [1] and [5].

3. THE SDE CONCEPT

In Software Defined Electronics every RF bandpass signal processing is substituted by an equivalent BB one implemented entirely in SW. The novelty of SDE concept is in the integration of three components into one solution:

- transformation between the RF band-pass and BB low-pass domains is performed by a universal HW device;
- BB equivalent of an application to be implemented is derived in a systematic manner;
- embedded operation, i.e., the universal HW transformer is embedded into a computing platform.

3.1 Universal HW device: Transformation between the RF Band-Pass and BB Low-Pass Domains

The generic block diagram of equivalent BB implementation is shown in Fig. 2. The analog RF bandpass signals $x(t)$ and $y(t)$, i.e., the real physical signals, are given in the RF band-pass domain. These signals are represented by their digitized complex envelopes $\tilde{x}[n] = x_I[n] + jx_Q[n]$ and $\tilde{y}[n] = y_I[n] + jy_Q[n]$, respectively, in baseband.

The transformation between the RF band-pass and BB low-pass domains is performed by the *universal RF HW device* or *transformer*, that extracts the I and Q components of complex envelope from the incoming RF band-pass signal, or reconstructs the RF band-pass signal from the I and Q components. The HW devices are referred to as *universal* because the same HW transformer is used to implement all applications without any modification.

There are three main categories of universal RF HW transformers

- integrated circuits;
- Universal Software Radio Peripheral (USRP) [3] developed for university education and radio amateurs;
- PXI-based test bench developed for professional applications.

Each version performs the transformation between the RF band-pass and BB low-pass domains, however, the

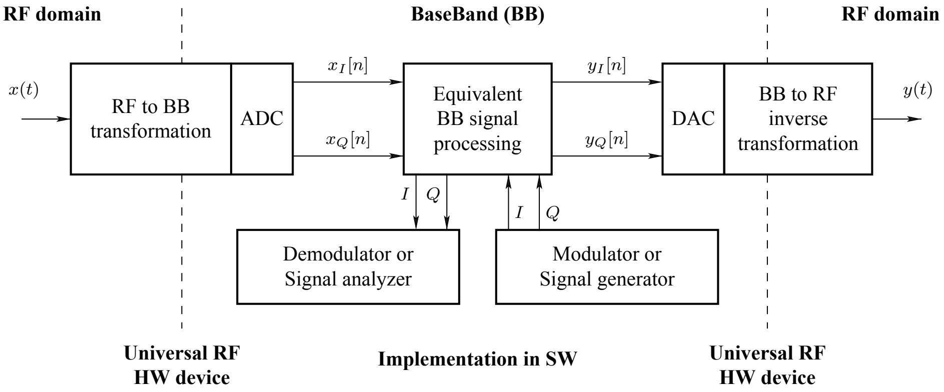


Figure 2. Generic block diagram of equivalent BB implementation. The transformations between the RF band-pass and BB low-pass domains are performed in both direction by the universal HW device.

integrated circuits do not offer a built-in HW/SW interface to connect the universal HW device to the host computer. The operation principles of the USRP- and PXI-based universal HW transformers are identical, but only the PXI device offers the accuracy required in measurement engineering. A short description of PXI-based HW transformer will be given in Sec. 4.4.

To illustrate the operation principle of universal HW transformer, the block diagram of MAX2769 integrated circuit is depicted in Fig. 3 where a quadrature mixer is used to extract the complex envelope of incoming RF bandpass signal connected to the "MIXIN" input and, after low-pass filtering and level controlling, two ADCs digitize the I/Q components.

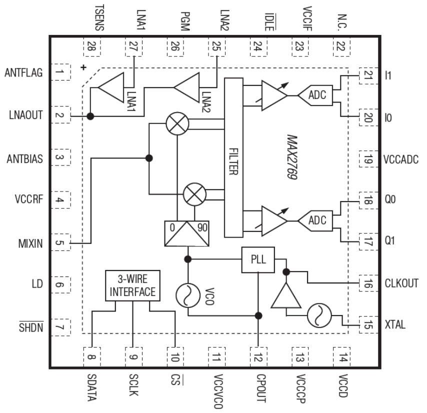


Figure 3. Transformation from the RF band-pass domain to BB: the block diagram of MAX2769 IC.

In SDE, every signal processing task is performed in BB by processing the digitized complex envelopes, and every application from demodulation to signal generation is implemented in BB and entirely in SW. The crucial issue is the derivation of BB equivalent of desired application.

3.2 Derivation of BB Equivalent

Two different approaches are available to derive the BB equivalents:

- mathematical derivation of BB equivalents [7], or
- transformation of the already known RF solutions into baseband.

Since the beginning of telecommunications, many solutions to different applications have been developed. If we want to re-use these already verified and proven solutions then the latter approach has to be used.

A systematic step-by-step approach for the derivation of BB equivalent from the RF band-pass model has been proposed in [8]. To show the way of transformation, the BB equivalent of an AWGN radio channel [1] is discussed here. Only the basic idea and the result of equivalent BB transformation are presented here, for all details and many more examples refer to [8].

The block diagram of RF AWGN radio channel is shown in Fig. 4 where $w(t)$ denotes the channel noise, K is the attenuation of radio channel, $s(t)$ and $r(t)$ are the transmitted and received signals, respectively. Since the SDE concept can be applied only to band-pass signals and systems, the bandwidth of channel noise $w(t)$ has to be limited by an ideal band-pass filter. If the bandwidth $2B_{noise}$ of this band-pass filter is greater or much greater than that of the transmitted signal $s(t)$ then the band limitation of channel noise does not restrict the validity of AWGN channel model.

First the BB equivalent of RF band-pass AWGN model has to be derived. Then the relationship between the parameters of RF band-pass noise and the Gaussian Pseudo Random Sequence Generators (PRSGs) used in BB to generate the BB equivalent of channel noise has to be found.

The BB equivalent of AWGN channel derived in [8] is depicted in Fig. 5. The BB equivalent includes the channel attenuation and two Gaussian PRSGs to

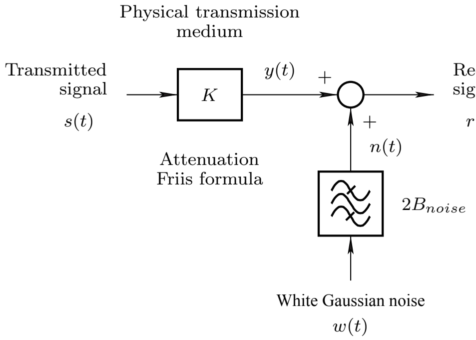


Figure 4. Block diagram of AWGN radio channel in the RF band-pass domain.

generate the I and Q components of channel noise. It is very important to note that the two PRSGs have to generate two *independent* PR sequences, otherwise the accuracy of BB equivalent is seriously corrupted.

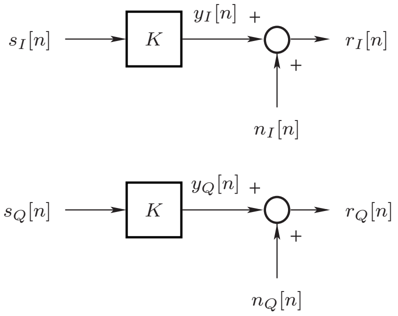


Figure 5. BB equivalent of AWGN radio channel.

The bandwidth of RF band-pass noise is determined by the BB sampling rate f_S

$$2B_{noise} = f_S$$

and the variances of two PRSGs have to be set to the noise power measured in the RF band-pass domain

$$\text{var}(n_I[n]) = \text{var}(n_Q[n]) = 2B_{noise}N_0 = N_0 f_S$$

where N_0 denotes the Power Spectral Density (psd) of white noise measured in the RF channel.

To verify the SDE concept, the AWGN channel was implemented in BB and the channel noise generated in BB was measured by a stand-alone spectrum analyzer in the RF band-pass domain. The psd of channel noise measured in the 2.4-GHz frequency band is shown in Fig. 6. As expected, the channel noise has a constant psd and its bandwidth is equal to the BB sampling rate.

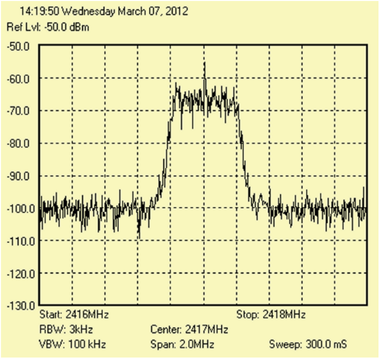


Figure 6. SW implementation of AWGN radio channel: psd of channel noise measured in the RF band-pass domain. The center frequency is 2.417 GHz.

3.3 Cascading of BB Equivalents

Every telecommunications system is constructed from signal processing blocks connected in cascade. Since cascading is preserved in baseband, a library of algorithms or a toolbox can be developed for the standard constituting blocks of telecommunications and measurement systems.

Consider a O-QPSK transmitter with a half-sine pulse shaping filter and assume that the transmitted O-QPSK signal travels to through an AWGN channel. The BB equivalent of AWGN channel is depicted in Fig. 5. Assume that our library has the BB equivalent of the O-QPSK transmitter.

Then the BB equivalent of the noisy O-QPSK signal generator can be constructed by connecting the BB equivalents of O-QPSK transmitter and AWGN channel in cascade as shown in Fig. 7 where $s_I^{O-QPSK}(t)$ and $s_Q^{O-QPSK}(t)$ give the I and Q components, respectively, of the output signal of O-QPSK modulator.

The LabVIEW-USRP SW-HW platform offers an easy way to implement BB equivalents because LabVIEW provides all drivers required by the USRP universal HW transformer. In LabVIEW, the BB implementation of each application is controlled via a Front Panel where the parameters of the desired application can be entered and the results can be visualized. The Front Panel of the noisy O-QPSK generator is shown in Fig. 8 where, addition to the I and Q components, both the constellation diagram (upper row, right) and the spectrum (lower row) of generated noisy O-QPSK signal are plotted.

The spectrum shown on the Front Panel have been calculated from the complex envelope in BB. The theory of complex envelopes claims that the BB representation does not generate any distortion and, except the carrier frequency, all information carried by the RF bandpass signal is also available in BB. This statement is true if the spectrum calculated from complex envelope in BB, see Fig. 8, and measured by a stand-alone

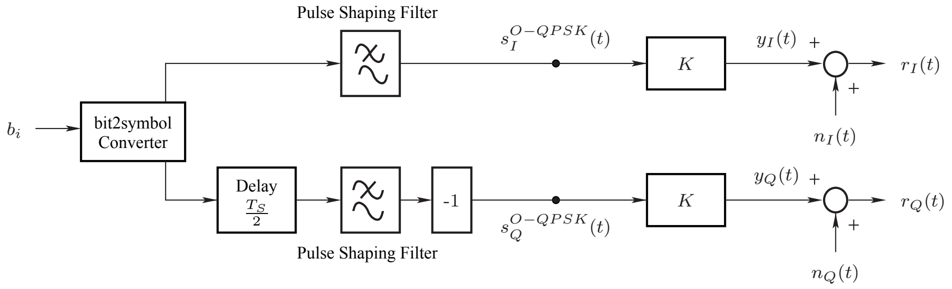
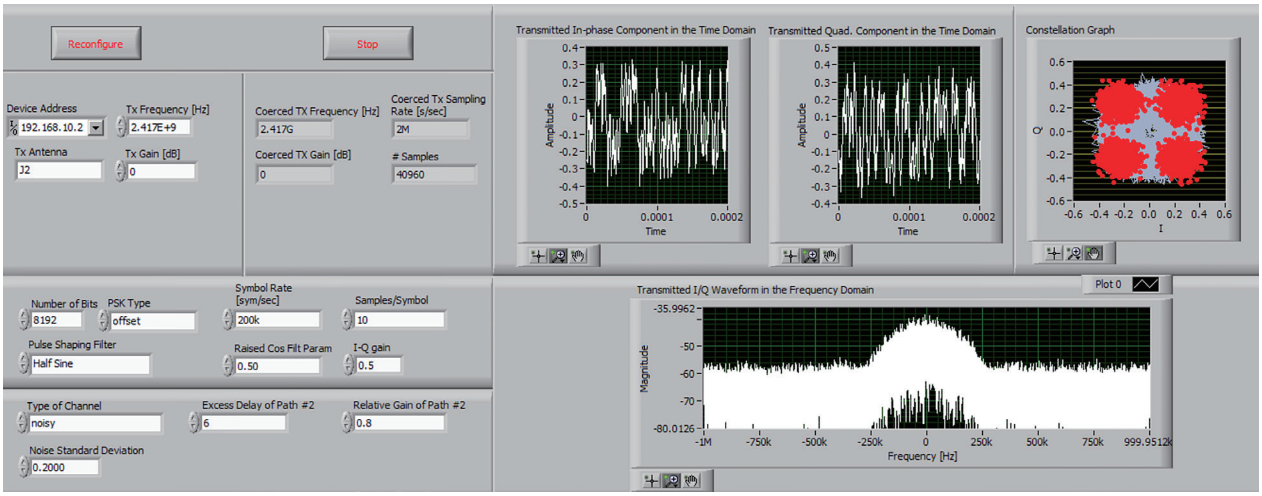


Figure 7. BB implementation of a noisy O-QPSK generator. Note, the I and Q outputs of O-QPSK transmitter are fed into the BB equivalent of AWGN radio channel.

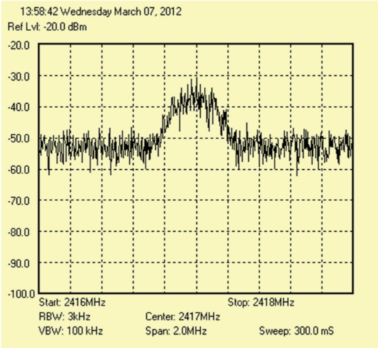


Device Address: 192.168.10.2
Tx Frequency [Hz]: 2.417E+9
Tx Antenna: J2
Tx Gain [dB]: 0
Coerced TX Frequency [Hz]: 2.417G
Coerced Tx Sampling Rate [s/sec]: 2M
Coerced TX Gain [dB]: 0
Samples: 40960
Number of Bits: 8192
PSK Type: offset
Symbol Rate [sym/sec]: 200k
Samples/Symbol: 10
Pulse Shaping Filter: Half Sine
Raised Cos Filt Param: 0.50
I-Q gain: 0.5
Type of Channel: noisy
Excess Delay of Path #2: 6
Relative Gain of Path #2: 0.8
Noise Standard Deviation: 0.2000

Figure 8. Front Panel of BB implementation of a noisy O-QPSK generator. The upper left and center waveform graphs show I and Q components, respectively, of complex envelope generated in BB. The upper right figure depicts the noisy constellation diagram while the lower one plots the spectrum of the noisy O-QPSK signal.

spectrum analyzer in the RF band-pass domain, shown in Fig. 9, are identical.

The comparison of Figs. 8 and 9 verifies the validity of equivalent BB transformation.



13:58:42 Wednesday March 07, 2012
Ref Lvl: -20.0 dBm
Start: 2416MHz
Stop: 2418MHz
RBW: 3kHz
Center: 2417MHz
VBW: 100 kHz
Span: 2.0MHz
Sweep: 300.0 mS

Figure 9. Measured spectrum of noisy O-QPSK signal. The measurement has been done by a stand-alone RF spectrum analyzer, the carrier frequency is 2.417 GHz.

3.4 Embedded Operation of Universal HW Device

The main feature of SDE concept is that any kind of telecommunications or measurement systems operating in the RF, microwave or optical frequency regions can be implemented entirely in SW. Consequently,

- at verification of a new research result there is no need to build an RF test bench which is a very expensive and time consuming task and needs a lot of special knowledge;
- during prototyping all parameters of the new system under development can be changed easily in SW.

The SW platform used for simulation can be integrated into a computing platform in the SDE concept, consequently, the simulator used in the research phase can be turned directly into a real working system and all field tests required can be performed without designing circuits or building a new HW.

The integration is achieved via the embedded operation where the structure of protocol stack architecture elaborated in IEEE Standard 802 is used. The universal HW device performing the transformation is considered as a physical (PHY) layer. To communicate with the application layer, the PHY offers two Service Access Points (SAPs): (i) one for configuration and (ii) another one for the transfer of complex envelope. The former SAP, referred to as "HW management SAP," is used to set the configuration parameters such as center frequency, power level, sampling rate, etc., while the latter one, referred to as "HW data service," provides the access to the I/Q sequences of complex envelope. The accessibility and use of these SAPs will be shown later, in Sec. 4.3.

4. USE OF SDE CONCEPT IN RESEARCH

Results achieved in scientific research are verified by computer simulation, mostly on MATLAB platform. The universal HW transformer processes the I/Q components of complex envelopes, consequently, any software capable of generating and processing the I/Q sequences can be integrated directly into the SDE platform. The complex envelopes provide the generic interface among the different SW platforms.

To illustrate the efficiency of SDE concept in scientific research, a MATLAB BB simulator is turned into a real radio system in this section.

4.1 FM-DCSK: An Unconventional Modulation

The transmitted radio wave propagates via many parallel paths from the transmitter to the receiver in indoor communications. The received signal components may be added in a destructive manner at the receiver which results in a deep frequency-selective multipath fading. To overcome the multipath propagation problem wideband signals are frequently used in indoor communications. The conventional solution is the spread spectrum approach [6] where the bandwidth of a narrow-band modulated signal is spread by a PR sequence.

Frequency Modulated-Differential Chaos Shift Keying (FM-DCSK) modulation [9] offers an alternative solution where the digital sequence to be transmitted is mapped into an inherently wideband chaotic carrier. Chaotic signals have no phase, frequency or amplitude, consequently, chaos-based communications systems cannot be implemented by re-using the building blocks of conventional telecommunications systems. Hence, FM-DCSK is a good example to demonstrate the flexibility of the SDE concept.

Since chaotic signals have no phase, frequency or amplitude, new modulation schemes have to be used in chaos-based communications. In FM-DCSK, each bit is mapped into two chaotic waveforms where the first waveform serves as a reference while the second one carries the digital information. If a bit "1" is transmitted then the information-bearing waveform is a delayed copy of the reference one. In case of bit "0," the information-bearing waveform is a delayed and inverted copy of the reference one.

The demodulator correlates the reference and information-bearing parts of the received signal and the decision is done according to the sign of correlation.

The implementation of the FM-DCSK radio link is broken into three steps in the SDE concept:

1) Starting from the original RF band-pass model of FM-DCSK radio link, first a MATLAB BB simulator is developed.
2) Because LabVIEW offers all drivers for the universal HW transformer, in the next step the MATLAB BB simulator is integrated into the LabVIEW platform.
3) Finally the FM-DCSK system is implemented on a PXI-based universal SDE platform.

4.2 Derivation of MATLAB BB Simulator

An FM-DCSK radio link includes three main building blocks:

- FM-DCSK transmitter;
- radio channel;
- FM-DCSK autocorrelation receiver.

The block diagram of the FM-DCSK radio link is shown in Fig. 10 where its main building blocks are also identified.

The binary information to be transmitted is denoted by b_i. The FM-DCSK receiver makes an estimation $\hat{b}_i$ of transmitted bits by observing the noisy received signal $r(t)$ for the observation time period T. Except two low-pass signals, namely the chaotic signal $m(t)$ in the transmitter and the observation signal $z(t)$ in the receiver, all signals shown identified in Fig. 10 are RF band-pass signals.

To get the BB equivalent, all RF band-pass signals of Fig. 10 have to be eliminated and the relationship between the two low-pass signals, the chaotic and observation signals, has to be established.

The FM-DCSK radio link is constructed from signal processing blocks connected in cascade. As discussed in Sec. 3.3 cascading in the RF band-pass domain is preserved in baseband, consequently, BB equivalents for each block of the FM-DCSK radio link can be developed independently from one another.

The BB equivalent of FM-DCSK radio link has been derived by a step-by-step process. The BB equivalent derived in [10] is depicted in Fig. 11. Note, the BB equivalent of FM-DCSK autocorrelation receiver includes two blocks, the channel filter and the FM-DCSK demodulator.

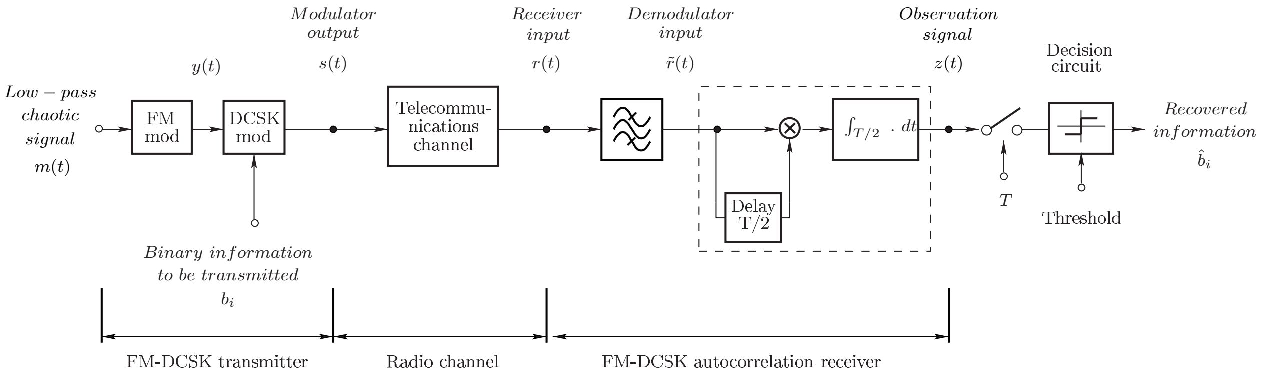


Figure 10. Block diagram of the FM-DCSK radio link in the RF band-pass domain. Note, the radio channel is also included.

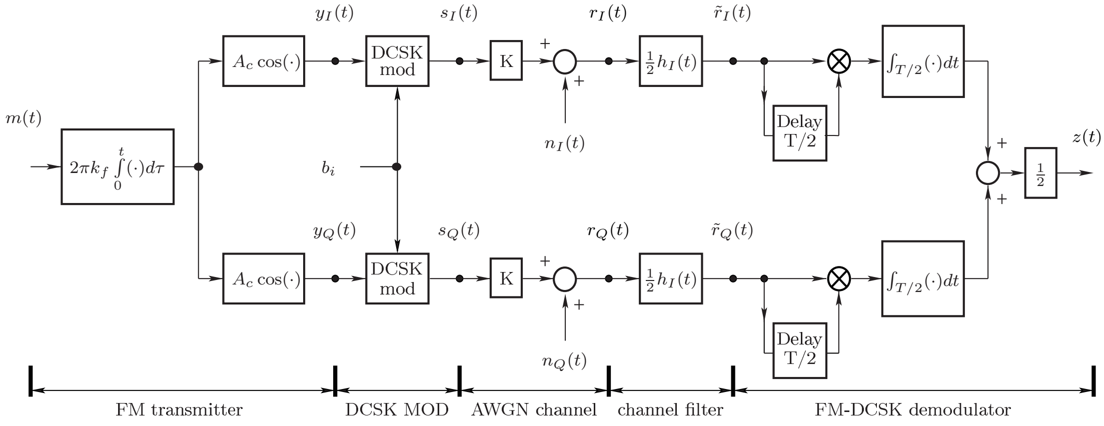


Figure 11. Baseband equivalent of the FM-DCSK radio link. Note, BB equivalent of radio channel is also included.

4.3 Integration of MATLAB into LabVIEW

As discussed in Sec. 3.4, the universal HW transformer constitutes the PHY layer of the computing platform. It can be reached via two SAPs, one of them is used for configuration while the other one serves to transfer the I/Q sequences of complex envelope.

The FM-DCSK radio link was implemented on a PXI-based universal SDE platform. All drivers for the universal HW transformer are available in LabVIEW, consequently, the LabVIEW was used to provide the SW interface between PHY and application layers. The BB equivalent of FM-DCSK radio link was implemented on MATLAB platform.

The crucial advantage of SDE concept is that the different SW platforms can be integrated into one application where the complex envelopes provide the interfaces between the different SW platforms.

To get a relatively simple block diagram, only the implementation of the FM-DCSK receiver is considered here. The transmitter and the radio channel have been implemented in the same manner.

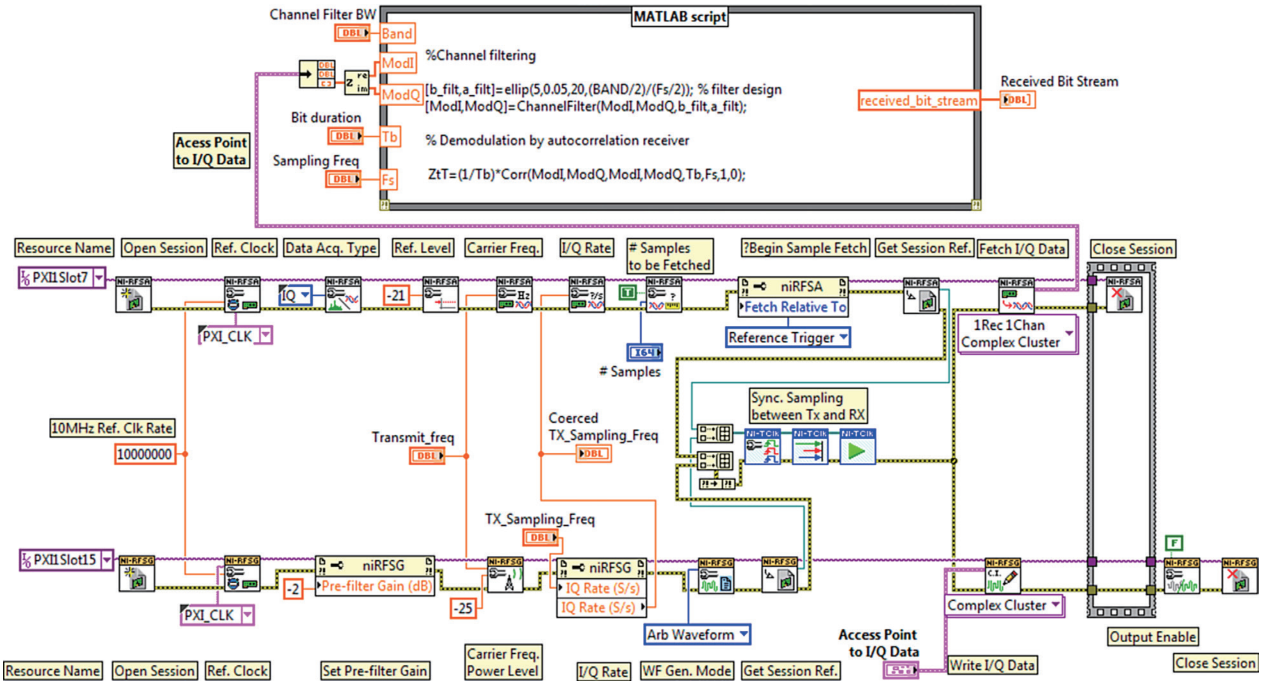
Figure 12 shows the block diagram of the implemented FM-DCSK receiver. The lower part of block diagram belongs to LabVIEW and is responsible for (i) the configuration of the universal HW transformers and (ii) fetching the I/Q data sequences. At the receiver side the I/Q components of the complex envelope are extracted by the block entitled "1Rec1Chan Complex Cluster" and uploaded into the MATLAB script via the "Access Point to I/Q Data" SAP.

The MATLAB script implements the FM-DCSK receiver, its elements are the "Channel filtering" and "Demodulation by autocorrelation receiver" algorithms. The MATLAB script returns the "Received bit Stream," from which the BER performance is evaluated and plotted.

Both the LabVIEW and MATLAB SWs have been installed and run on the same host computer.

4.4 PXI-Based Universal SDE Platform

The PCI eXtensions for Instrumentation (PXI) is an industrial modular instrumentation architecture elaborated by the PXI Systems Alliance [11]. It offers



```
%Channel filtering

[b_filt,a_filt]=ellip(5,0.05,20,(BAND/2)/(Fs/2)); % filter design
[ModI,ModQ]=ChannelFilter(ModI,ModQ,b_filt,a_filt);

% Demodulation by autocorrelation receiver

 ZtT=(1/Tb)*Corr(ModI,ModQ,ModI,ModQ,Tb,Fs,1,0);
```

Figure 12. Block diagram of the FM-DCSK radio link implemented in SW. Note, the MATLAB script which implements the FM-DCSK receiver is integrated into the LabVIEW environment.

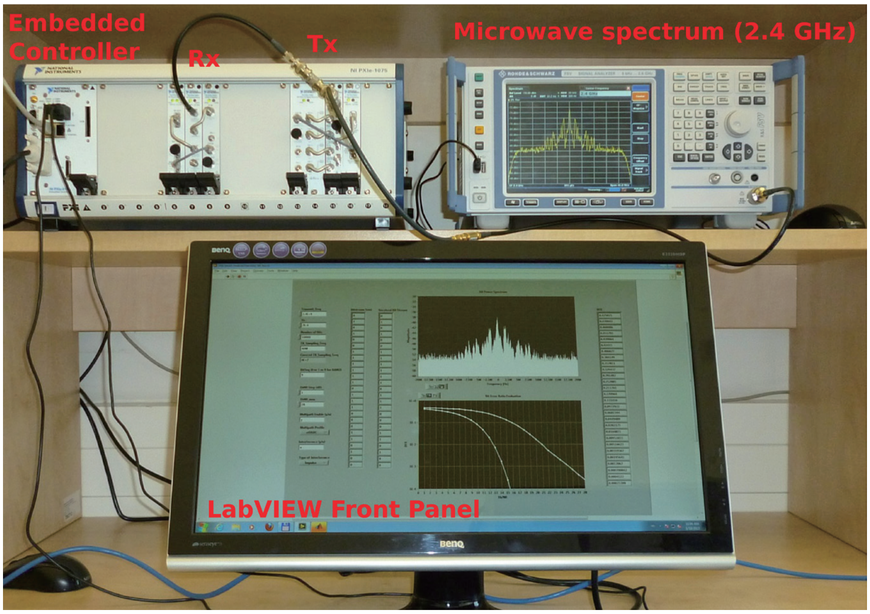


Figure 13. Photo of the PXI-based universal SDE platform. The PXI chassis and the stand-alone microwave spectrum analyzer are on the top-left and top-right, respectively, of the photo while the monitor in the bottom visualize the LabVIEW Front Panel.

building modules for flexible, PC-based and high-performance measurement and automation systems. Like the Lego toy, any measurement, control or automation system can be constructed from the PXI off-the-self modules available on the market.

Photo of the PXI-based universal SDE platform is shown in Fig. 13. That testbed is suitable for the implementation of any telecommunications and measurement engineering applications up to 6.6 GHz entirely in SW. The components of testbed are as follows:

- the PXI chassis, shown on the upper left part of the photo. The chassis includes an embedded controller and two universal HW transformers;
- a stand-alone microwave spectrum analyzer used to check the real-world RF band-pass signals;
- a monitor, identified as "LabVIEW Front Panel," used to control the SDE platform and visualize the BB signals and test results.

The SDE implementation of FM-DCSK radio link includes the blocks plugged in the PXI chassis:

- an embedded controller, see the left block in the PXI chassis.
  The embedded controller provides the computing HW platform for both MATLAB and LabVIEW. It is connected to the other blocks of PXI chassis via a high speed PCIe interface.
- universal HW device, see the block in the middle of PXI chassis, marked by "Rx."
  This block extracts the I/Q sequences of complex envelope from the incoming RF band-pass signal and uploads them into the embedded controller via the PCIe interface.
- universal HW device, see the right block in the PXI chassis, marked by "Tx."
  This block reconstructs the RF band-pass signal from the I/Q sequences generated in BB by the SWs run on the embedded controller.

Figure 13 shows the automated BER performance evaluation of FM-DCSK radio system both in an AWGN radio channel and in a noisy multipath environment. Both the FM-DCSK radio transceiver and the noisy radio channels are implemented in baseband and entirely in software.

The upper figure of LabVIEW Front Panel shows the spectrum of received signal travelling via the noisy multipath channel. Both channel noise and effect of multipath propagation, i.e., the multipath-related, deep frequency-selective fading can be observed.

The spectrum visualized on the LabVIEW Front Panel was determined in BB by evaluating the I/Q sequences extracted from the received noisy and corrupted signal. The spectrum shown by the microwave spectrum analyzer was recorded in the RF band-pass domain by measuring the real 2.4-GHz microwave signal. The identity of the two spectra proves that the SDE concept does not involve any distortion.

Lower figure of the LabVIEW Front Panel shows the measured BER performance of FM-DCSK transceiver in (i) an AWGN and (ii) a noisy multipath radio channel. The PXI-based universal SDE platform has an implementation loss of 0.7 dB which is the noise contribution of local oscillators, RF amplifiers and DAQ converters used in the universal HW transformers.

Figure 13 reveals a unique feature of the SDE concept, namely, that many parallel signal processing tasks being run simultaneously on the same host computer can be implemented. In our example the same received noisy and corrupted signal is used both (i) to demodulate the transmitted data stream and (ii) to measure the spectrum of received FM-DCSK signal. In radio communications this feature enables the simultaneous reception of transmitted information and the evaluation of channel conditions without interrupting the data traffic.

5. NEED FOR CHANGE IN TEACHING PARADIGM

Teaching paradigm of RF radio communications systems does not match the industry expectations because telecommunications engineering of our times

- relies on the integration of many disciplines from signal processing to FPGA programming. In engineering curriculum these topics are taught as independent subjects, even worse, many times using different terminologies.
- is becoming more and more complex where the main emphasis is on the integration and system level analysis. The universities still focus on teaching the different subjects in an isolated manner and leave the problem of system level integration to the students.
- uses off-the-self IC blocks implemented according to the SoC concept. The design and manufacturing of these HW devices are concentrated at a few places, the majority of our graduates will never design HW devices. Instead, they should have a solid background in system level design.
- goes software defined. Our graduates should have an applicable skill in software defined implementations.
- needs more laboratory experiments in the university curriculum to narrow the gap between the theory and practice.

The problems can be solved or, at least alleviated considerably, if the SDE concept is introduced into the university education and the teaching paradigm of RF radio communications is changed accordingly. The SDE concept uses a top-down approach and focuses on integration and system level engineering. In SDE everything is software defined, consequently, the direct relationship between the theory of signal processing and SW implementation is highlighted clearly. Because there is no need to design and build HW devices, the students can design and implement their application in SW and then they can evaluate the performance of their systems in the lab. The same universal SDE platform can be used in each subject, consequently, cost of lab experiments can be kept low and students have to learn the use only of one universal SDE platform.

6. CONCLUSIONS

SDE concept integrates many already known solutions into one unified theory in order to get a universal SW defined platform for the implementation of RF telecommunications and measurement systems. This paper has provided an overview of the SDE concept and showed its use in scientific research.

In the SDE concept every application is implemented in baseband and universal HW transformers are used to perform the conversion between the RF band-pass signals measured in the real world and their BB equivalents, the digitized low-pass complex envelopes. The BB signals are processed entirely in SW, consequently, every application is implemented in SW.

The equivalent BB implementation relies on the complex envelopes that assures the lowest sampling rate attainable theoretically to process a band-pass signal without loosing any information or suffering from any distortion.

The SDE approach offers a very high level of flexibility where either the functionality or the parameters of an application can be changed in SW, even dynamically. This feature

- is a must in many emerging applications such as cognitive radio, adaptive systems, etc.;
- makes the verification of scientific research results possible because the computer simulator used to verify the new theoretical result can be turned into a real working system;
- reduces the time-to-the-market considerably in industry because there is no need to re-design the HW during prototyping. Any change to be done needs only to modify the software;
- helps in education to fulfill the gap between the theory and practice because the students can design and implement any kind of real working telecommunications and test systems in the lab.

Another unique feature of SDE concept is that many parallel signal processing tasks can be implemented and run simultaneously on the same host computer. For example, the received signal can be used not only to recover the transmitted information but also can be considered as a test signal to determine the channel conditions.

The SDE concept relies on the transformation performed between the RF band-pass and low-pass BB domains. The transformation is done by universal HW devices, consequently, the same HW transformer is used in every application. To make the already proven RF band-pass solutions re-usable, a systematic step-by-step process has been elaborated for the derivation of BB equivalents.

Real world RF band-pass systems are constructed from blocks connected in cascade. In the SDE concept cascading is preserved in BB, consequently, a library of frequently used building blocks can be developed.

The SDE concept makes the integration of different SW and HW platforms into one solution possible. Then a universal SDE testbed can be developed where every application can be implemented on the same universal SDE platform by changing only the SW in the application layer.

To prove the efficiency of the SDE concept, the paper has shown (i) how a PXI-based universal SDE platform can be developed and (ii) how a BB MATLAB FM-DCSK radio link simulator can be integrated into the PXI-based universal SDE platform.

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