2015 International Symposium on Nonlinear Theory and its Applications
NOLTA2015, Kowloon, Hong Kong, China, December 1-4, 2015

University Ivory Tower: To Stay in or Break Out SDE: A Direct Jump from Scientific Research to Industrial Applications

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Abstract—New results achieved in scientific research carried out at universities are verified almost exclusively *only* by computer simulations. The universities very rarely have the necessary skill, access to IC technology and financial support to turn a new idea into a real-word working system. This approach puts the university research into an ivory tower and develops a gap between university research and industrial applications.

Software Defined Electronics (SDE) offers a solution to this challenge if *band-pass* signals are used to carry the information. The band-pass property makes the substitution of each RF/microwave/optical analog signal processing possible with a low-frequency digital one. In SDE all 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 transformer in every application. The software defined implementation provides that huge level of flexibility which is a must in scientific research and the SDE concept generates and processes all real-world physical signals required to verify the new idea in a real application scenario.

1. Introduction

Because of the high implementation cost, results of scientific researches conducted at universities are verified almost exclusively by computer simulations. However, this approach suffers from a very serious basic problem: if the same mathematical model is used in both the research and verification phases and if the model is inaccurate, for example, it neglects important implementation or application dependent effects, then the computer verification provides false or misleading results and in a real application scenario the new idea developed will fail to work or will not achieve the performance improvement predicted by the computer simulations.

This simulation oriented approach puts university research into an ivory tower and develops a gap between academia and industry. The verification of our new research results with stand-alone equipment and in real application environments is a must if our society wants to keep its leading role in researching new ideas, systems and solutions. To bridge the gap between university research and industrial applications a university-friendly solution has to be found.

The Software Defined Electronics (SDE) concept offers a solution to this problem for the class of *band-pass* signals and systems. In SDE, the band-pass signals and systems are transformed into BaseBand (BB) by a universal HW device and every application is implemented in BB, entirely in software. All BB equivalents are low-pass signals and blocks, and the BB equivalents carry all information which is available in the original band-pass signals. Hence, every information carried by the physical band-pass signals can be recovered in BB, and every band-pass signal processing algorithm has its own BB equivalent. The main features of SDE concept are as follows:

- it requires the lowest sampling rate attainable theoretically;
- it does not introduce any kind of distortion or loss of information;
- it uses the same *universal* HW device in every application to perform the transformation between the BB data sequences generated and processed by a computer program and the physical signals measured in the real world.

The SDE concept exploits the idea of embedded systems. The computer simulator developed for and used in research is run in the application layer. If the simulator is capable to generate and process the data sequences in BB then the BB sequences can be transformed into real-world physical signals by the universal HW transformers embedded into the same computing platform and the real-world physical signals can be measured, the performance of the new idea proposed can be evaluated by stand alone test equipment. Even real field tests can be performed if the physical signals reconstructed by the universal HW device are used in an already operating network or application.

The software defined approach provides the huge level of flexibility required in research because each parameter or even the system configuration can be changed in SW and there is no need to design and implement a new and expensive HW. Note, this level of flexibility is also essential in many industrial applications from cognitive radio to reconfigurable adaptive systems.

The SDE concept integrates many ideas and practices used in mathematics to handle band-pass signals and systems [1], software defined radio [2]-[3], embedded systems, virtual instrumentation [4] into one solution. The new contributions of SDE concept are as follows:

- many already known ideas are put into a unified framework;
- the relationship between the real world and equivalent BB domain is defined as a transformation performed by universal HW device operating in an embedded manner;
- solutions implemented on different SW platforms can be integrated into one single application;
- a step-by-step process has been developed for the derivation of BB equivalents.

Section 2 surveys the mathematical background of SDE concept, it defines the complex envelopes and summarizes the properties of equivalent BB implementation. The SDE concept is discussed in Section 3 where it is interpreted as a transformation performed between the real-world band-pass and the low-pass BB domains. A step-by-step method is given for the derivation of BB equivalents and the embedded operation of universal HW transformers is also discussed.

Our main goal is to turn a simulator used in scientific research directly into an operating system that can be used even in an already operating network or application. This issue is discussed in Section 4 where a MATLAB BB simulator developed for studying FM-DCSK modulation scheme is turned into a real-world digital radio transceiver operating in the 2.4-GHz ISM frequency band.

The recent trend in ICT is that everything goes software defined. 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. The industry specific issues are surveyed in Section 5.

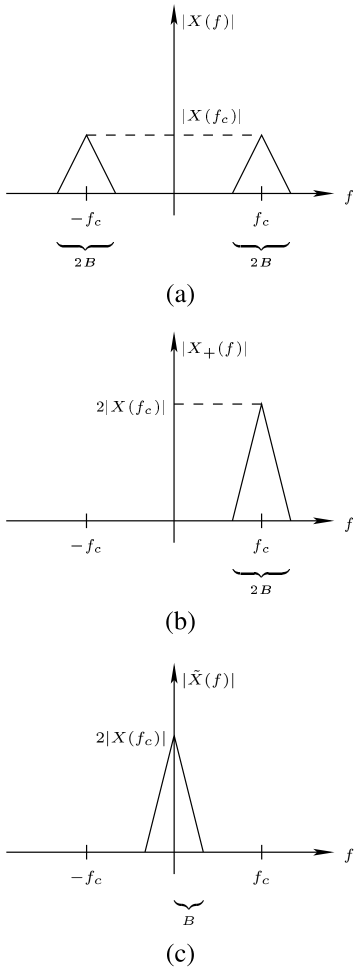
Telecommunications and test systems of our times (i) are becoming more and more complex, (ii) everything is software defined and (iii) operates in an embedded manner. Since every application is implemented in SW, the main challenge is not in the circuit design but in the integration of many different 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 in electrical engineering has to be changed. Section 6 is devoted to this issue, i.e., the university education.

2. Mathematical Background: Baseband Equivalents

Band-pass signals are used in many applications to convey information either in communications or measurement engineering. 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 *complex envelopes* and *equivalent baseband transformation*.

2.1. Complex Envelopes

The idea of equivalent BB representation can be applied to *band-pass* signals and systems. Consider a RF real-valued band-pass signal $x(t)$ and assume that the spectrum $X(f)$ of $x(t)$ is zero or negligible out of the RF bandwidth $2B$ centered about the center frequency $\pm f_c$ as shown in Fig. 1(a). Note, in case of a modulated signal f_c is referred to as carrier frequency.



(a)

(b)

(c)

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 a product

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

where the *complex envelope* $\tilde{x}(t)$ is a complex-valued function and $\Re$ denotes the real-part operator. The real and imaginary parts of the slowly-varying complex envelope

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

are referred to as the in-phase and quadrature components (denoted by I and Q), respectively.

The derivation of complex envelope can be better understood 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).

Recall, each real-valued signal has a two-sided spectrum that cannot be shifted directly to BB. To solve the problem a one-sided spectrum has to be formed by defining the pre-envelope as

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

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 band-pass 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 of each band-pass system needs to consider three basic constituting components:

- deterministic signals discussed already 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 of these constituting components. 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 relationships between the RF band-pass and BB low-pass domains are summarized in Fig. 2 where the amplitude spectra of an RF band-pass deterministic signal, the amplitude responses of an LTI block and the power spectral densities (psd) of a random process are plotted in both the RF band-pass and BB low-pass domains. Note the simple rule of thumb: every RF band-pass property becomes low-pass in baseband.

3. The SDE Concept

In Software Defined Electronics every RF bandpass signal processing is substituted by an equivalent BB one implemented entirely in SW. In SDE three components are integrated 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. This approach allows the integration of an off-the-self software (for example, a simulator used in scientific research) into the SDE implementation of a new application where the reused SW is run in the application layer.

The generic block diagram of equivalent BB implementation is shown in Fig. 3. The analog RF bandpass signals $x(t)$ and $y(t)$, i.e., the real-world physical signals, are available 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 derives the I and Q components of complex envelope from the incoming RF band-pass signal and, in the opposite direction, reconstructs the RF band-pass signal from its I and Q components. The HW devices

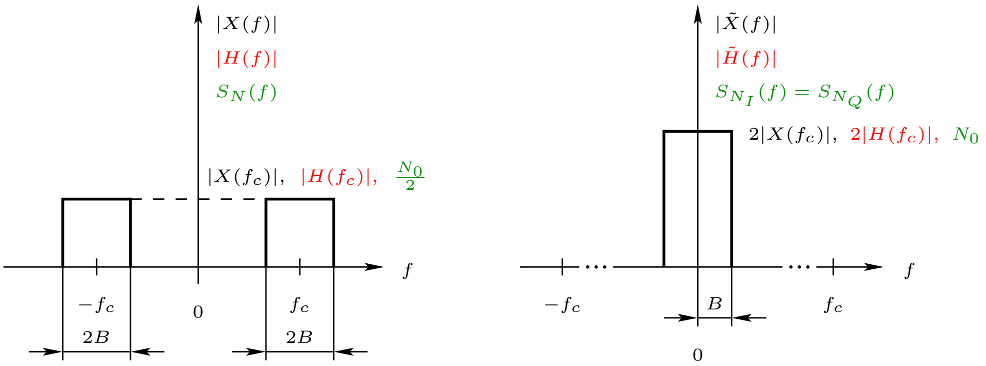


Figure 2: Relationship between the RF band-pass and BB low-pass domains: $|X(f)|$, $|H(f)|$ and $S_N(f)$ are the amplitude spectrum of a deterministic signal, amplitude response of an LTI block and psd of a random process, respectively, in the RF band-pass domain. Their BB equivalents are denoted by $|\tilde{X}(f)|$, $|\tilde{H}(f)|$, $S_{N_I}(f)$ and $S_{N_Q}(f)$.

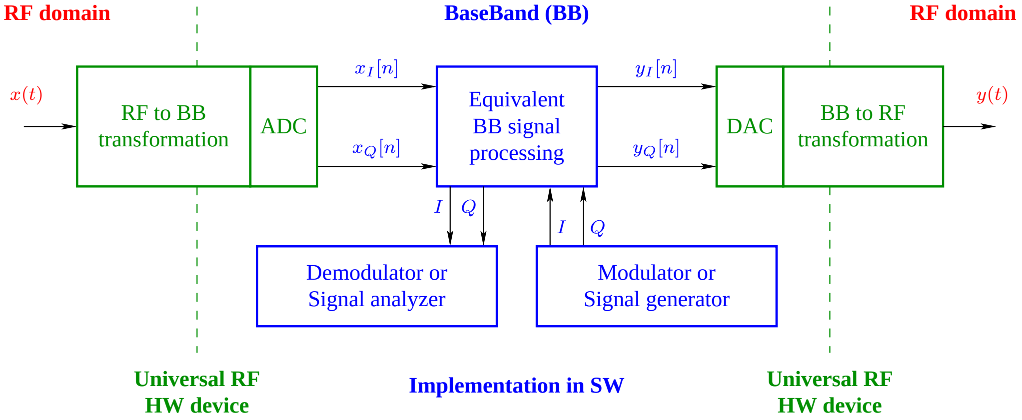


Figure 3: Generic block diagram of equivalent BB implementation. The transformations between the RF band-pass and BB low-pass domains are performed in both directions by the universal HW device.

are referred to as *universal* because the same HW transformer is used to implement all applications without any modification.

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

In a mathematical sense, the universal HW transformer performs the transformations between the RF band-pass and BB low-pass domains. It can be considered as a circuit implementation of a mathematical transformation. As shown in Fig. 4, the mathematical scheme developed to derive the in-phase and quadrature components from an RF band-pass signal includes two multipliers referred to as quadrature mixer in circuit theory, two low-pass filters and two amplifiers [1]. The I and Q components of complex envelope available at the outputs of two amplifiers are still analog signals, $x_I(t)$ and $x_Q(t)$ are converted into BB data sequences by two analog-to-digital converters. Then the BB data sequences $x_I[n]$ and $x_Q[n]$ are uploaded from the universal HW transformer into the application layer and processed in SW to implement the desired application. Note, the universal HW device performs two tasks: (i) it derives the I/Q components of the incoming RF band-pass signal and then (ii) it digitizes them and returns the I/Q data sequences.

The mathematical scheme required to reconstruct an RF band-pass signal from the I/Q BB sequences is even simpler, addition to the two digital-to-analog converters it needs two mixers and an analog summer as depicted in Fig. 5 [1]. Note again the two tasks performed: (i) conversion of I/Q sequences into two analog signals and (ii) reconstruction of the RF band-pass signal.

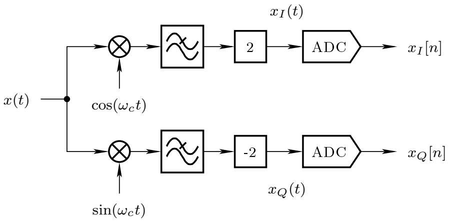


Figure 4: Mathematical scheme for the derivation of complex envelope of an RF bandpass signal.

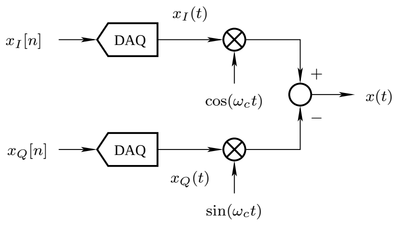


Figure 5: Mathematical scheme for the reconstruction of an RF bandpass signal from its complex envelope.

There are three main categories of universal RF HW transformers:

- integrated circuits;
- Universal Software Radio Peripheral (USRP) 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 integrated circuits do not offer a built-in HW/SW interface to connect the universal HW device to a 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. More details on the PXI-based HW transformer will be given in Sec. 4.4.

To illustrate the operation principle of universal HW transformers, let the block diagram of a MAX2769 integrated circuit depicted in Fig. 6 be compared with the mathematical scheme shown in Fig. 4. Note, first the MAX2769 IC derives the complex envelope of incoming RF bandpass signal connected to the "MIXIN" input as analog I/Q signals then, after level controlling, the I/Q components are digitized, and finally the $x_I[n]$ and $x_Q[n]$ sequences are sent to the IC's output pins.

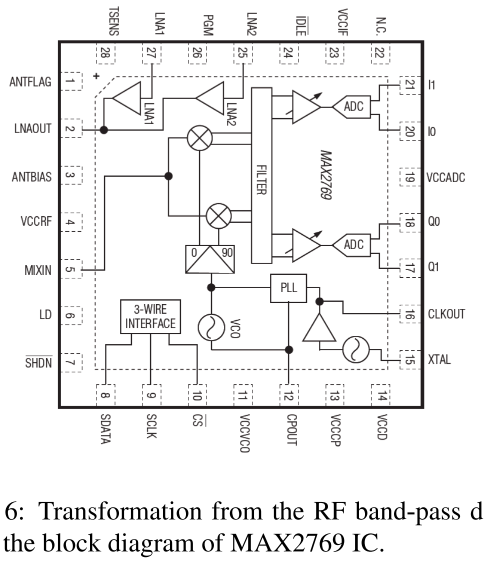


Figure 6: Transformation from the RF band-pass domain to BB: the block diagram of MAX2769 IC.

3.2. Derivation of BB Equivalent

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

Two different approaches are available to derive the BB equivalents:

- mathematical derivation of BB equivalents as a signal processing algorithm [7], or
- transformation of the already known RF solutions into a baseband equivalent.

In electrical engineering and signal processing, many solutions to different demands have been developed. If we want to reuse these already widely applied 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 illustrate the main steps of derivation, 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 an RF Additive White Gaussian Noise (AWGN) radio channel is shown in Fig. 7 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 Gaussian white 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.

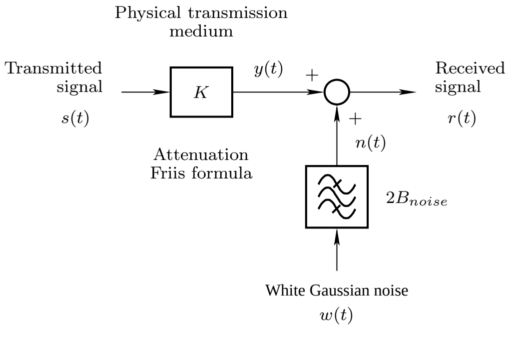


Figure 7: Block diagram of AWGN radio channel in the RF band-pass domain.

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. 8. The BB equivalent includes the channel attenuation and two Gaussian PRSGs to generate the I and Q components of channel noise. It is very important to note that the two PRSGs have to generate two *uncorrelated* PR sequences containing statistically independent samples. Otherwise, the accuracy of BB equivalent is seriously corrupted.

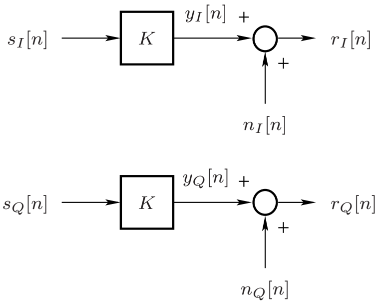


Figure 8: BB equivalent of AWGN radio channel.

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

$$2B_{noise} = f_S \tag{2}$$

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

$$\mathrm{var}(n_I[n]) = \mathrm{var}(n_Q[n]) = 2B_{noise}N_0 = N_0 f_S. \tag{3}$$

In the equation above, N_0 denotes the psd of white noise measured in the RF channel.

To verify the SDE concept, the AWGN channel was implemented in BB and SW using the block diagram of Fig. 8. The parameters of channel noise were set according to (2) and (3). Then, a universal HW transformer was used to reconstruct the analog RF band-pass channel noise from the I/Q BB sequences.

The psd of channel noise measured in the 2.4-GHz ISM frequency band by a stand-alone spectrum analyzer is shown in Fig. 9. As expected, the channel noise has a constant psd and its bandwidth is equal to the BB sampling rate.

3.3. Cascading of BB Equivalents

Every measurement, telecommunications or information processing 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.

Consider an O-QPSK transmitter with a half-sine pulse shaping filter and assume that the transmitted O-QPSK signal travels through an AWGN channel. Recall, the BB equivalent of AWGN channel has been already depicted in Fig. 8. The library published in [8] has the BB equivalent of O-QPSK transmitter.

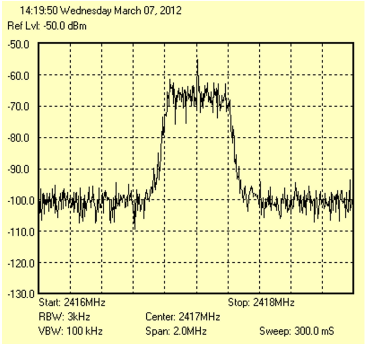


Figure 9: SW implementation of AWGN radio channel: psd of channel noise measured in the RF band-pass domain. The center frequency is 2.417 GHz.

The BB equivalent of the noisy O-QPSK signal generator is constructed by connecting the BB equivalents of O-QPSK transmitter and AWGN channel in cascade as shown in Fig. 10. The I/Q sequences $r_I[n]$ and $r_Q[n]$ of the noisy O-QPSK signal are generated by the BB equivalent in SW and the I/Q sequences are processed by the universal HW transformer to reconstruct the RF bandpass signal $s(t)$.

The NI LabVIEW platform offers a convenient way to implement BB equivalents because LabVIEW provides all drivers required by the universal HW transformers. In LabVIEW, the BB implementation of each application is controlled via a graphical user interface referred to as *Front Panel* where the parameters of the desired application can be entered and the results calculated in BB can be visualized. The Front Panel of the noisy O-QPSK generator is shown in Fig. 11 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. Note, all signals generated and processed in LabVIEW and visualized on the Front Panel are data sequences defined in BB.

The theory of complex envelopes claims that the BB representation does not generate any distortion and, except f_c, all information carried by the RF band-pass signal is also available in BB. To verify this statement the identity of the two spectra (i) calculated from complex envelope in BB and (ii) measured by a stand-alone spectrum analyzer in the RF band-pass domain has to be checked.

The LabVIEW Front Panel, depicted in Fig. 11, gives the spectrum calculated from the BB data sequences, while the spectrum measured by a stand alone spectrum analyzer is shown in Fig. 12. Note, the two spectra are identical, verifying the validity of equivalent BB transformation. The effect of channel noise can be clearly recognized in each figure: Gaussian clouds develop about the four QPSK message points in the constellation diagram and the uniform psd of channel noise appears in the spectra calculated in BB and measured in the RF band-pass domain.

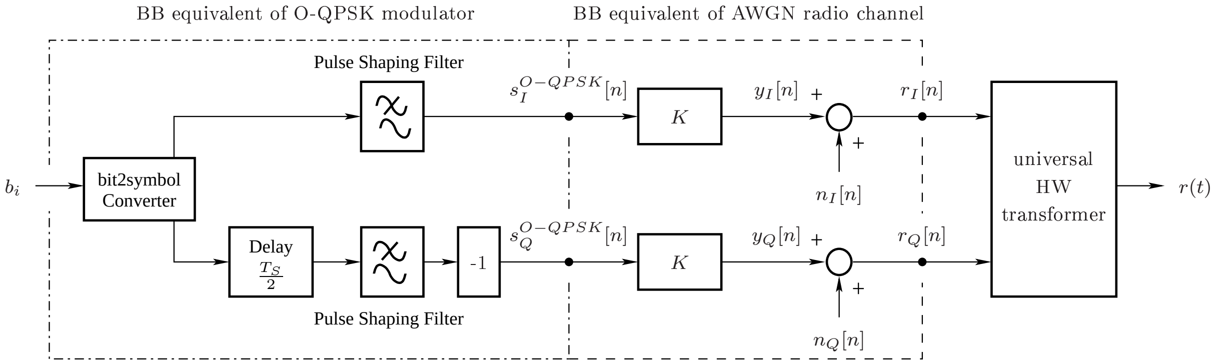
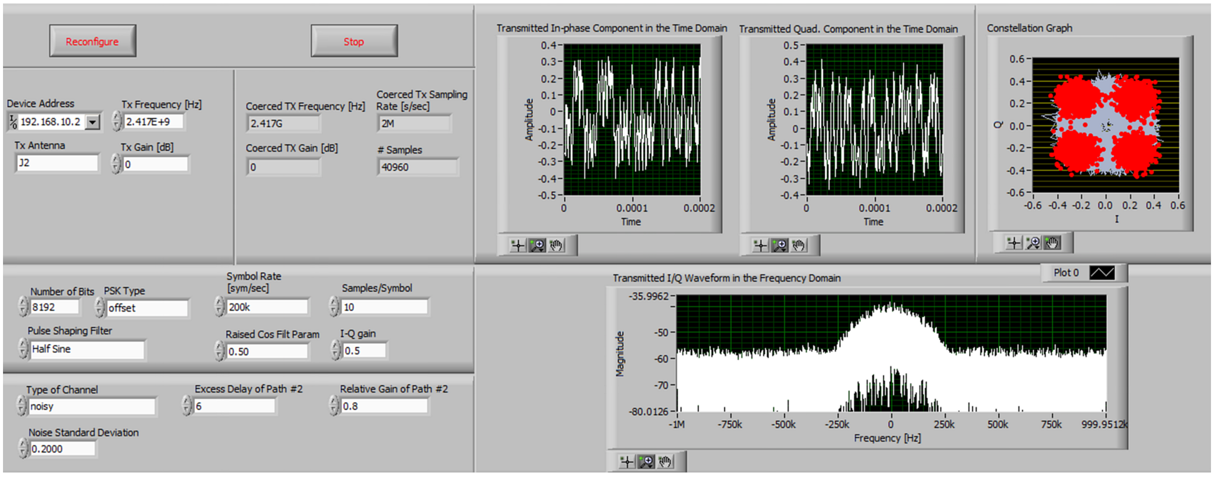


Figure 10: SDE implementation of a noisy O-QPSK system. The BB equivalent of noisy O-QPSK signal is generated in SW by a noiseless O-QPSK modulator and AWGN channel connected in cascade in BB. The real-world RF band-bass signal *s*(*t*) is reconstructed by the universal HW transformer from the *I* and *Q* sequences given by $r_I[n]$ and $r_Q[n]$.



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 11: 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.

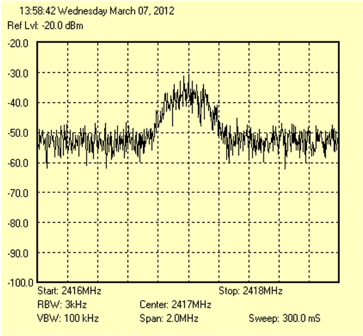


Figure 12: Measured spectrum of the noisy O-QPSK signal. The measurement has been done by a stand-alone RF spectrum analyzer, the carrier frequency is 2.417 GHz.

3.4. Embedded Operation of Universal HW Device

The main feature of SDE concept is that any kind of the *band-pass* telecommunications, measurement and information processing 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 research or prototyping all parameters of the new system can be changed easily in SW.

The SW platform used for simulation can be integrated into the SDE concept, consequently, every BB simulator used in the research phase can be turned directly into a real working system and all verifications and field tests required can be performed without designing new 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 universal HW device 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 to convey the information. 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, the well-known conventional modulation schemes cannot be applied and chaos-based communications systems cannot be implemented by reusing the building blocks of conventional telecommunications systems. Hence, FM-DCSK is a good example to demonstrate the applicability and flexibility of SDE concept.

Since amplitue-, phase- and frequency-shift keying modulations cannot be used in chaos-based communications, new modulation schemes have been elaborated. In FM-DCSK, the most efficient, robust and popular modulation scheme, 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. 13 where every signal and each constituting block of the FM-DCSK radio link are 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 RF band-pass 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 in Fig. 13 are RF band-pass signals.

To get the BB equivalent, all RF band-pass signals of Fig. 13 have to be expressed by their complex envelopes and the relationship between the two low-pass signals, namely, the chaotic and observation signals, has to be established in BB.

As shown in Fig. 13, the FM-DCSK radio link includes many 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.

Originally the BB equivalent of the FM-DCSK radio link was derived to develop a MATLAB simulator. The simulator was necessary in the research phase to verify the feasibility of the FM-DCSK radio transceiver and to determine its BER performance in both AWGN and multipath radio channels [9]. Universal HW devices and the SDE concept were not available at that time, the MATLAB simulator was developed in BB just to minimize the simulation time.

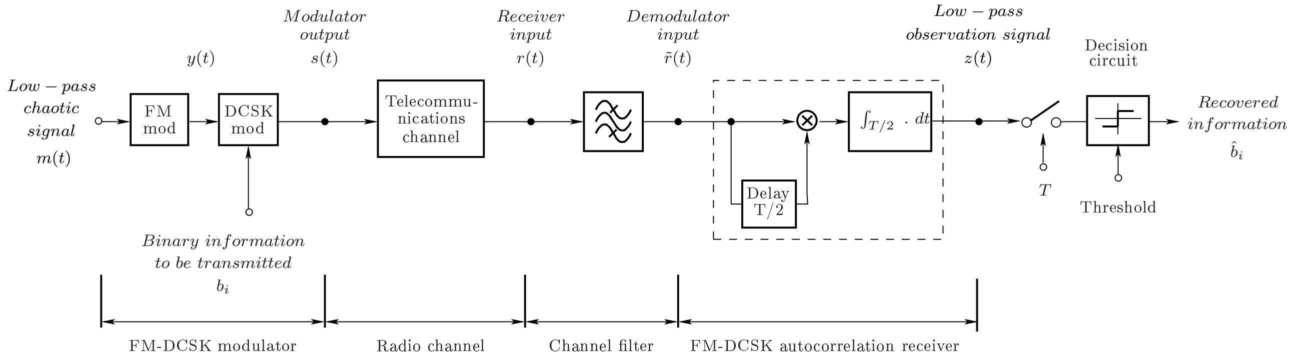


Figure 13: Block diagram of the FM-DCSK radio link in the RF band-pass domain. Note, the radio channel is also included and except the chaotic signal *m*(*t*) and the observation signal *z*(*t*) all waveforms are RF band-pass signals.

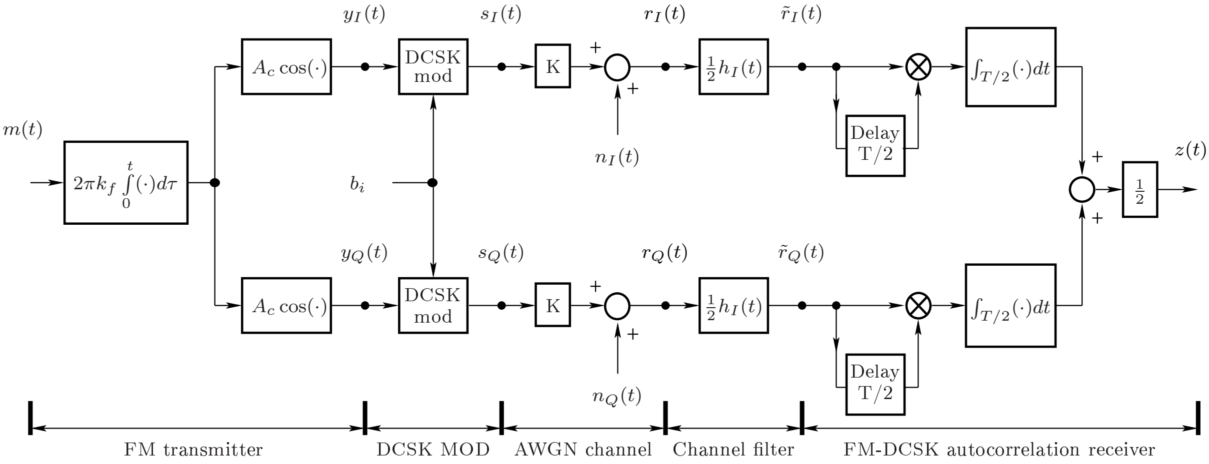


Figure 14: Baseband equivalent of the FM-DCSK radio link. Note, BB equivalent of radio channel is also included.

The equivalent BB model is depicted in Fig. 14, for the details of its derivation refer to [10]. To simplify the models and to get a figure which is easy to interpret, only the analog signals are shown in Figs. 13 and 14. The parameters of digitization were chosen in such a way in the MATLAB BB simulator that the digitization did not introduce any distortion.

To illustrate the use of SDE concept in research, next paragraph will discuss how the MATLAB BB simulator can be turned into a working FM-DCSK radio receiver *without any modification*. As shown in Fig. 14, the BB equivalent of FM-DCSK receiver includes two blocks, the “Channel filter” and the “FM-DCSK autocorrelation receiver.”

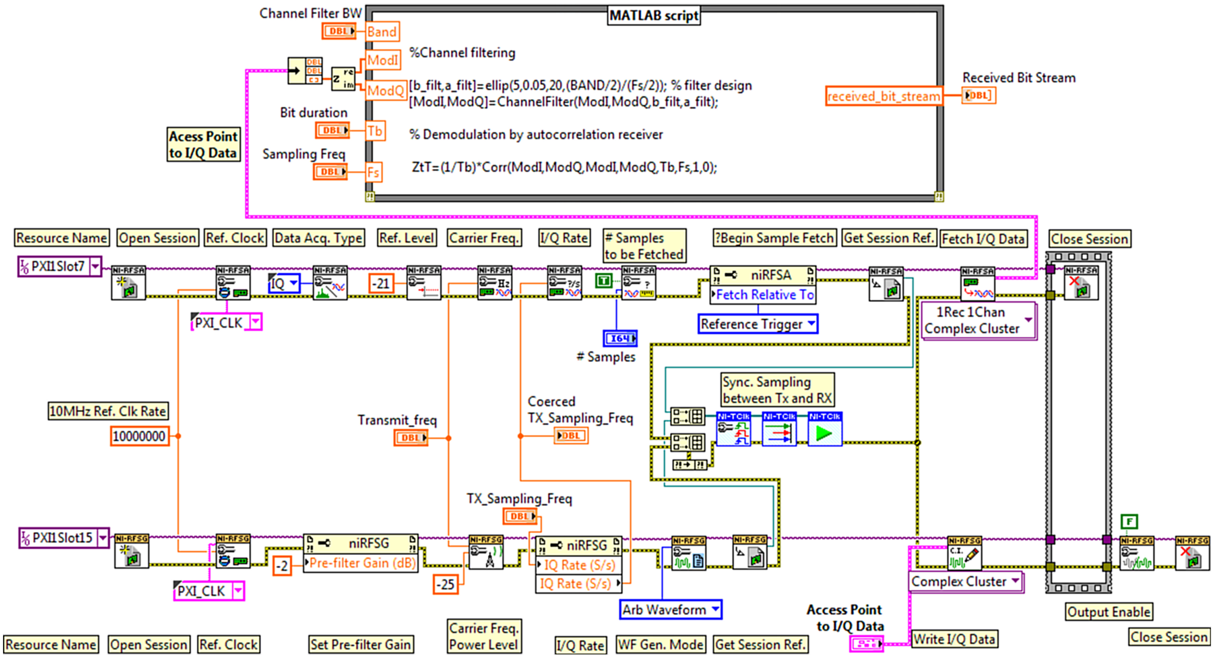
4.3. Integration of MATLAB into LabVIEW

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 chosen to provide the SW interface between the PHY and application layers. The BB equivalent of FM-DCSK radio link was implemented by the MATLAB BB simulator, i.e., 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 among the different SW platforms. Figure 15 shows the block diagram of the implemented FM-DCSK receiver where the lower part of block diagram shows the LabVIEW interface to the universal HW transformer. From the left to the right first the parameters of universal HW device are set and then the I/Q components of the complex envelope are extracted from the received RF band-pass signal by the block entitled “1Rec1Chan, Complex Cluster.” Finally, the I/Q sequences are uploaded into the MATLAB script via the “Access Point to I/Q Data” SAP.

The MATLAB script implements the FM-DCSK receiver, its algorithms are: “Channel filtering” and “Demodulation by autocorrelation receiver.” The MATLAB script returns the “Received bit Stream,” from which the BER



```
%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 15: 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. The "Channel filtering" and "Demodulation by autocorrelation receiver" algorithms of MATLAB BB simulator are used in the MATLAB script.

performance is evaluated and plotted.

Both the LabVIEW and MATLAB SW platforms have been installed and run on the same host computer. Note the crucial advantage of SDE concept: it turns the MATLAB BB simulator developed in the research phase into a working system that is capable to generate and process the real-world physical signals. These signals can be measured by stand-alone equipment, can be used to perform all field tests and can be radiated into an existing network to evaluate the performance of the new system proposed in a real-world environment. Even more, the algorithms of a BB simulator can be used directly, without any modification, in the SDE implementation.

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 building modules for flexible, PC-based and high-performance measurement and automation systems. 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. 16. That testbed is suitable for the implementation of any telecommunications and measurement engineering applications 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 following blocks plugged in the PXI chassis:

- embedded controller, see the left block in the PXI chassis.
  The embedded controller provides the computing 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 derives the I/Q sequences 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 SW run on the embedded controller.

Figure 16 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

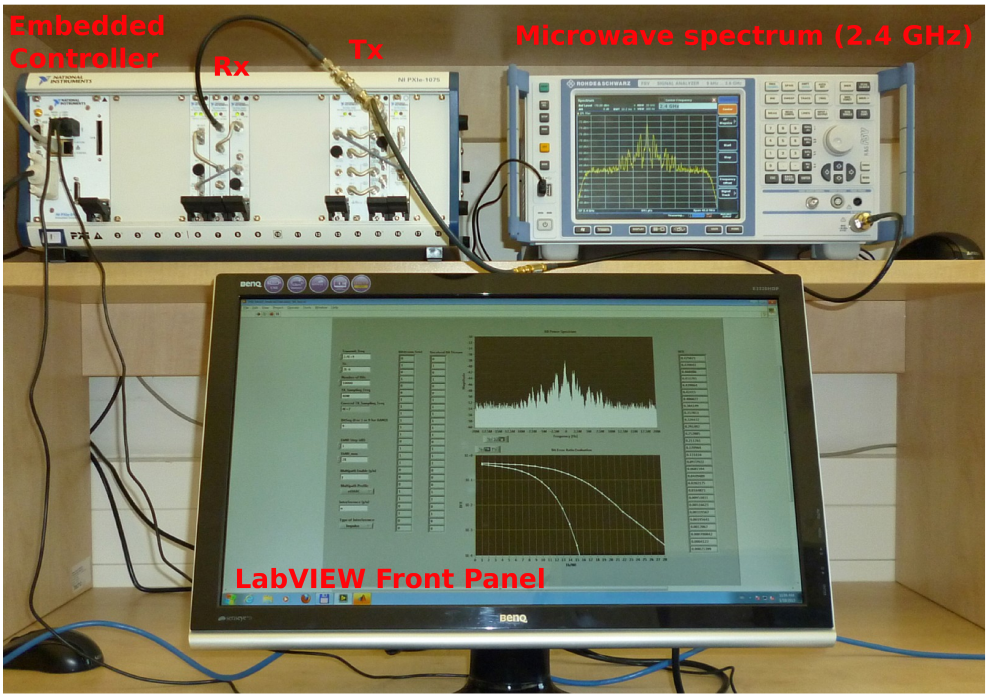


Figure 16: Photo of the PXI-based universal SDE platform. The PXI chassis and the stand-alone microwave spectrum analyzer are on the top-left and top-right, respectively, of the photo while the monitor in the bottom visualizes the LabVIEW Front Panel.

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 the 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. However, the spectrum shown by the microwave spectrum analyzer was recorded in the RF band-pass domain by measuring the real-world 2.4-GHz microwave signal. The identity of the two spectra verifies the SDE concept and proves that it does not introduce 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 ADC and DAC modules used in the universal HW transformers.

Figure 16 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. Industry demands: low-cost, flexibility, multifunctionality and embedded operation

Industry demands always have been (i) low production and prototyping cost, (ii) short time from product planning to market release and (iii) simple and cheap modification of a product during its manufacturing life time. In our time new requirements are arising, let the most important ones listed here:

- because of the continuous and rapid change in standards, technology and/or applications the products already used have to be updated and modernized regularly;
- new applications and services have to be implemented on the same, already widely used products;
- certain applications such as cognitive radio rely on the multifunctional use of the same HW platform;
- adaptivity is a must in many applications;
- market demands frequently cannot be identified in advance before releasing a new product. After evaluating the market response, new services and applications have to be implemented on the already sold devices.

The old and new requirements summarized above can be satisfied if a universal HW platform is used and the different applications are implemented entirely in SW. A good example for this trend can be observed in instrument industry where, instead of physical circuits, the concept of virtual instrumentation is used to implement the signal processing algorithms. Another important issue is that more and more applications are embedded into a computing platform. The last great challenge is that the systems and applications used today are becoming more and more complex.

The skill of university graduates has to meet these industry demands. Every year less and less engineers are working on the development of new HWs and ICs but more and more are developing applications in SW for standard universal HW platforms. This trend has been well known in the low frequency applications for many years and, in recent time, the rapid development in technology has enabled the extension of SW defined approach up to even the optical frequency range.

6. Need for Change in Teaching Paradigm

University teaching paradigm does not match the industry demands discussed above because electrical engineering is still taught in the conventional way where

- a bottom-up approach is used. The circuit theory is taught first, then a lot of attention is devoted to the design of circuits and HW blocks and the curriculum is finished by teaching FPGA implementation;
- different subjects are taught in an isolated manner, independently of one another. To make the problem even tougher, the different subjects are discussed by using different terminologies;
- system level engineering is not taught, unity of mathematics and engineering is not highlighted;
- young unexperienced students are expected to understand system level design and integration themselves without any guidance.

To follow the changes in ICT industry, electrical engineering should be taught in an opposite way, using a top-down approach. After laying down the foundations in mathematics and information processing, the education should be started at system level engineering and the main emphasis should be laid on the following topics:

- system level integration where the same terminology should be used in each subject;
- implementation of complex systems from off-the-self HW blocks. A little attention should be given to the design and manufacturing of circuits and HW devices because the majority of our graduates will never design HW devices;
- implementation of different applications entirely in SW. Our graduates should have an applicable skill in software defined implementations;
- analysis and design of embedded systems;
- more laboratory experiments should be involved in university curriculum to narrow the gap between the theory and practice.

Subjects taught in the conventional curriculum such as microwaves, optics, filters, etc. should be discussed but only in that extent which is necessary to perform system level analysis and design.

In the area where band-pass signals carry the information, the problem can be solved if the SDE concept is introduced into the university education. The SDE concept uses a top-down approach and focuses on integration and system level engineering. In SDE every application 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 own 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 of *only one* universal SDE platform.

The SDE concept can also be used to bridge the gap between scientific research and practice because every BB simulator used in the research phase can be turned directly without any extra efforts into an operating system. This approach was presented in Section 4 where a MATLAB BB simulator developed in 1998 to verify the feasibility of FM-DCSK modulation scheme [10] and used in 2000 in research to evaluate its system performance in a noisy multipath channel [12] has been reused recently, without any modification, to implement an operating FM-DCSK radio transceiver.

7. Conclusions

SDE concept integrates many already known solutions into one unified theory in order to get a universal software defined platform for the implementation of band-pass information processing 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 a 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 redesign 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 reusable, 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 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. 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 in scientific research, 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 turned into a real-world radio transceiver.

Acknowledgments

This research was financed by the Pázmány Péter Catholic University under the grant number KAP-15-160-5.2-ITK and KAP-3, and was supported by Yiannis Pavlou, the Academic Director of National Instruments in Europe. The author would like to express his deepest gratitude for the help and continuous support.

Tamás Krébesz has played a crucial role in the elaboration of the SDE concept and he carried out all measurements used to verify the concept. His contributions have been essential and are highly appreciated.

This plenary talk was invited by the NOLTA 2015 Organizing Committee. This is the very first time when a comprehensive material on the SDE concept is published. The author would like to thank this great opportunity.

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