Universal Portable SDE Platform for Teaching the Theory and Practice of ICT Systems

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***Abstract*—A universal portable software defined electronics platform developed to teach info-communications systems is proposed here. Because every application is implemented in software, the universal platform is suitable for the implementation and simulation of any kind of communications or measurement systems where the information is carried by band-pass signals. The software defined electronics platform needs only a laptop and two universal software radio peripheral devices, and it can be used everywhere without a laboratory infrastructure.**

I. Introduction

There are many excellent textbooks [1]–[5] that discuss the theory of ICT systems. However, those books cover only the theory and discusses a lot of details which are hard to be understood by students. Some laboratory experiments are used to complete the theoretical studies but, because of the limited lab resources, those experiments are too simple, the students cannot change the system configurations and they cannot try their own design. As a result, a wide gap develops between the theory and practice of ICT systems in education.

The universal portable Software Defined Electronics (SDE) platform proposed here can solve this problem. It is universal because any kind of ICT systems where the information is carried by band-pass signals can be implemented on this platform, and it is portable because it can be used everywhere even without a lab infrastructure.

Comprehensive study of digital communications can be broken into three levels:

1) *Theory of waveform communications:* mapping of symbols into analog waveforms, transmission of digital information over a band-limited channel, intersymbol-interference, Nyquist channel, estimation of transmitted symbol at the receiver, that is, demodulation;
2) *Turning the theory into real working systems,* implementation of ICT applications;
3) *Study of complete radio links:* real-world analog signals at the transmitter and receiver, propagation of radio waves, models of radio channels, evaluation of overall system performance, bit-error rate, sources of errors.

The SDE examples presented here correspond to these levels. At Level 1 simulators are used to demonstrate the theory of digital communications including the effect of channel conditions. At Level 2 stand-alone applications are implemented which pick up their input signal by an antenna and process this real-world physical signal. At Level 3 a complete operational M-ary FSK radio link is implemented and tested.

In SDE concept every application is implemented in software. This approach equips the SDE platform with a huge flexibility, even the students can implement their own ICT systems. It can be also used in prototyping and research where a computer simulator used to verify a research result can be turned directly into a working communications system [6].

II. Concept of Universal SDE Platform

In general, band-pass signals are used in ICT systems to carry the information. In SDE, every application is implemented entirely in SW and universal RF HW transformers are used to establish the transformation between the analog band-pass signals measured in the real world and the data sequences processed and generated in baseband [7].

To implement an application in SW, the real-world analog signals have to be digitized or reconstructed from their samples. The crucial issue is the sampling rate, it has to be minimized without corrupting or loosing the information carried by the real-world analog band-pass signals. The lowest sampling rate attainable theoretically can be achieved by using the theory of complex envelopes [1] and equivalent BaseBand (BB) transformation [8].

A. Complex Envelope and BB Equivalents

To get the minimum sampling rate, the RF band-pass signal $x(t)$ is decomposed into a product of a complex envelope $\tilde{x}(t)$ and a center frequency ω_c

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

where $\Re$ is the real-part operator [1]. When a modulated signal is considered then ω_c is referred to as the carrier frequency. Except ω_c, the complex envelope preserves all information carried by $x(t)$, therefore, every RF band-pass signal processing can be substituted by its BB equivalent relying on the complex envelopes. Note, $\tilde{x}(t) = x_I(t) + jx_Q(t)$ is a complex valued waveform, its real and imaginary parts are referred to as in-phase (I) and quadrature (Q) components.

Because ω_c has been removed, the complex envelope is a low-pass signal and its bandwidth is equal to the half of the bandwidth $2B$ of RF band-pass signal. Consequently, the required sampling rate in BB does not depend on ω_c, it is determined exclusively by B. It is a crucial advantage because $B << \omega_c/2\pi$ in real applications.

BB equivalents are available for (i) deterministic signals, (ii) LTI blocks and (iii) random processes, that is, for all constituting elements of a linear system.

B. General Block Diagram of Equivalent BB Implementation

Block diagram of SDE concept is shown in Fig. 1 where the real-world RF band-pass analog signals and the BB data sequences are plotted in red and blue, respectively. Note, the RF band-pass signals $x(t)$ and $y(t)$ are represented by the I and Q components of their complex envelopes in BB. The digitized versions of I and Q components are denoted by $x_I[n]$–$y_I[n]$ and $x_Q[n]$–$y_Q[n]$, respectively.

The SDE theory is a generalization of Software Defined Radio (SDR) concept [9] where the SDE concept can be used to implement any kind of band-pass applications. In SDE, the transformations

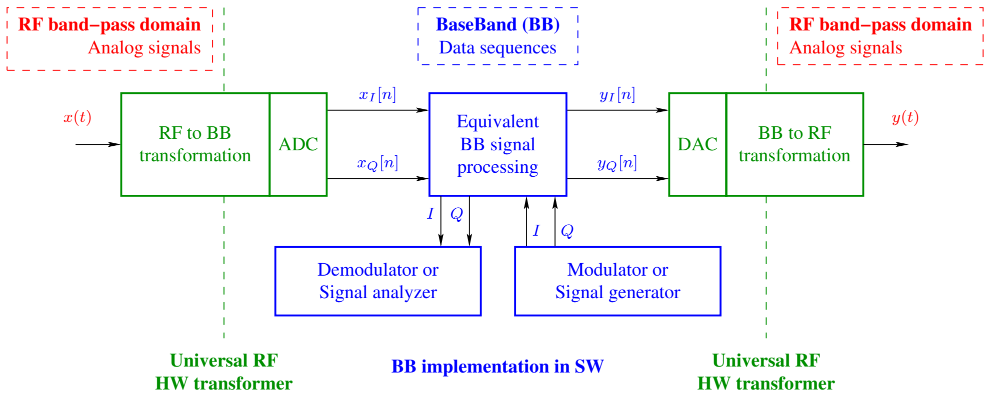

Figure 1. General block diagram of equivalent BB implementation.

between the RF band-pass and BB low-pass domains are performed by the *universal RF HW transformers* shown in green in Fig. 1.

The SDE concept relies on BB equivalents, that is, on the equivalent BB representations of original RF band-pass problems. In SDE, each RF analog band-pass signal processing task is fully substituted by an equivalent low-pass digital one defined in BB. Distortion does not occur, information is neither lost nor distorted.

Two different approaches are available in the literature to derive the BB equivalents:

1) *mathematical derivation* of BB equivalents [5], or
2) *transformation of an already known RF band-pass system* into a digitized BB equivalent.

To eliminate the gap between theory and practice, the second approach is preferred in engineering schools. Furthermore, Approach 2 allows to re-use the already proven solutions known from the literature. A step-by-step process for the derivation of a BB equivalent from a RF band-pass block diagram has been proposed in [8].

C. Transformation between the analog RF band-pass and digital BB low-pass domains

The transformation between the RF analog band-pass and digital low-pass BB domains is performed in both directions by universal HW transformers shown in green in Fig. 1. These devices are universal because the *same transformers* are required in each application and the implementation of a new application needs to change only the SW used in BB.

A universal HW transformer performs two tasks: (i) the transformation between the RF band-pass and BB low-pass domains and (ii) ADC or DAC conversion.

III. Portable SDE Platform

Our goal was to develop a portable SDE platform which can be used everywhere, even in classrooms and not only in labs, to implement any kind of ICT systems. The SDE concept has been used because it offers that level of flexibility which we need in education. In SDE, every application is implemented entirely in SW, therefore, the students can change each parameter of the ICT system under study, including even its configuration and block diagram. Even more, the students can implement and test their own solutions.

To fulfill these requirements a universal portable SDE platform has been developed which needs only one laptop and two RF HW transformers. The photo of our SDE platform is shown in Fig. 2 where a 4-FSK radio link is tested. The constituting parts of the SDE platform are as follows:

- the SW which is run on the laptop in baseband;
- one universal RF HW transformer for the transmitter (Tx) and another one for the receiver (Rx);
- the transmit (Tx) and receive (Rx) antennas;
- USB cables which connects the universal RF HW transformers to the laptop, that is, to the computing platform.

The SDE platform uses two Universal Software Radio Peripheral (USRP) devices as RF HW transformers. The real-world analog RF band-pass signals are fed into and are available from the front-panel SMA connectors (see Tx USRP on the left) while the digitized complex envelope is available at the rear-panel USB connector (see Rx USRP on the right). These USRP devices can be used from 70 MHz up to 6 GHz.

The two applications, that is, the 4-FSK transmitter (Tx) and 4-FSK receiver (Rx), are implemented in BB and entirely in SW run on the laptop. The two Front Panels shown on the laptop screen provide graphical interfaces to the SW. All data and waveforms are controlled and/or visualized on the Front Panels. The 4-FSK signal is radiated into the air by the Tx transmit antenna and picked up by the Rx receive antenna.

IV. Teaching ICT Systems via Hands-on-Examples

To follow the three-level study of ICT systems discussed in Sec. I, six hands-on-examples have been elaborated:

1) two simulations at system level;
2) SDE implementations of two stand-alone applications;
3) SDE implementations and testing of a complete radio link where real antennas and radio channels are used.

The demonstrations start with the verification of the theory of waveform data communications. At Level 2 stand-alone applications are implemented and tested with real-world physical signals picked up by an antenna. At Level 3 a complete digital radio link is implemented and tested.

The three-level step-by-step approach leads the students from the theory to the implementation, and helps them to understand the operation principle, design rules and practice of ICT systems. Students have access to the computer programs written in an easy-to-understand graphical programming language. Each SW from the system level simulators to the SDE implementation of complete radio links relies on the complex envelopes. The only difference is that the transformation between BB and RF domains is not performed in the simulators, consequently, USRP transformers are not used at Level 1.

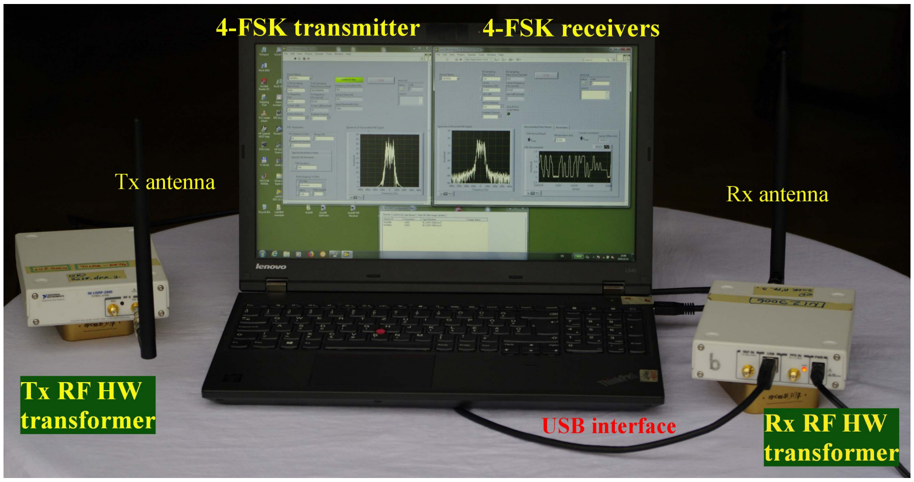

Figure 2. Universal portable SDE platform testing a 4-FSK radio link.

A. Simulation at system level

At Level 1 the theory of digital waveform communications is taught and verified. Here each simulator works in BB and the real-world physical signals are not used. All signals and their spectra are visualized, and all parameters of a radio link can be changed from the Front Panel. The effect of each system parameter on system performance can be seen immediately.

Figure 3 shows the Front Panel of a BPSK simulator which implements a BPSK transmitter, a BPSK receiver and the radio channel. White Gaussian noise is added to the received signal in the radio channel and a limiter is used to demonstrate the effect of its nonlinearity. The plotted figures are as follows:

1) from left to right, upper row: spectrum of transmitted BPSK signal, spectrum of the noisy received signal and the noisy received signal in the time domain;
2) from left to right, lower row: spectrum of noisy received signal after channel filtering, eye diagram and constellation diagram.

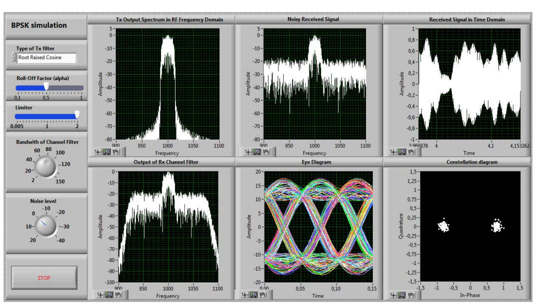

Figure 3. Front Panel of BPSK simulator where a random binary sequence is transmitted. Effects of channel noise, filtering and nonlinearity can be also studied.

The following phenomena can be studied:

- spectral forming by the transmit filter;
- intersymbol interference, conditions of Nyquist channel;
- effect of channel select filtering;
- communications in AWGN channel;
- nonlinear distortion and spectral re-growth.

A *continuous* pseudo-random data stream is transmitted in the BPSK simulator shown in Fig. 3. However, the majority of digital communications systems transmits frames. Therefore, the next simulator demonstrates the operation of a *burst-mode* M-ary QAM radio link.

Front Panel of a M-ary QAM simulator is shown in Fig. 4. The communications is performed in an AWGN radio channel and the following signals and spectra are visualized:

- I and Q components of transmitted noise-free and received noisy complex envelopes;
- constellation diagrams of transmitted noise-free and received noisy signals;
- spectrum of noisy received signal;
- preamble and structure of one frame;
- I and Q inputs of the decision circuit.

All parameters of a M-ary QAM radio link can be changed from the Front Panel. For more details and description of each waveform zoom-in into Fig. 4.

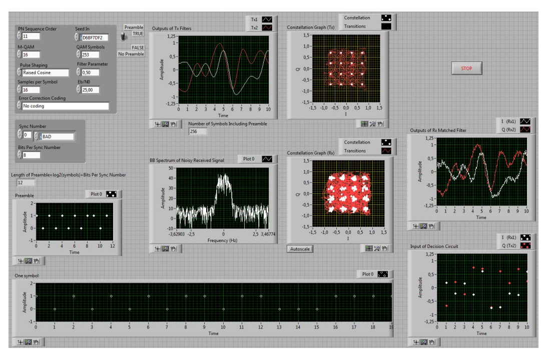

Figure 4. Front panel of the M-ary QAM simulator with an AWGN channel.

B. SDE implementations of stand-alone applications

At Level 2 single stand-alone applications are implemented and tested on the portable SDE platform. These applications use only one USRP HW transformer but *process real-world analog RF band-pass signals* picked up by the antenna. These demonstrations (i) help the students to understand the operation principle of a spectrum analyzer and an analog FM receiver and (ii) verify that the SDE approach really can be used to implement any kind of real ICT applications.

The spectrum analyzer is used to scan the FM radio broadcasting band. After selecting an FM radio station, the FM broadcasting is

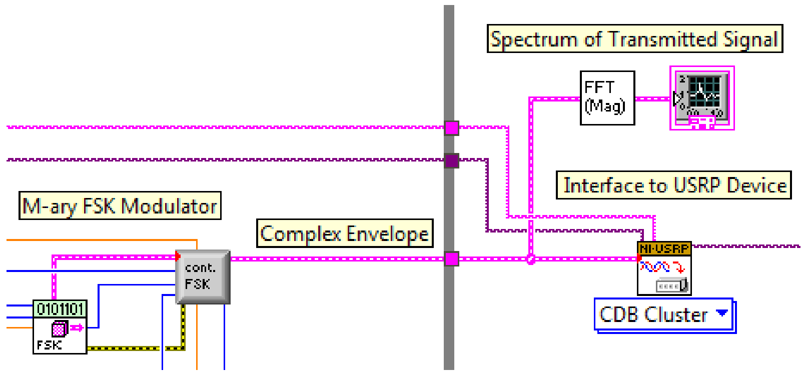

Figure 7. Part of software used to implement the 4-FSK transmitter. The complex envelope of 4-FSK signal is fed into the driver of USRP device which provides interface to it (see "NI-USRP" block) via the USB cable. The complex envelope is also used to visualize the spectrum of transmitted signal in BB.

received by another SDE application and the demodulated FM signal is send to the audio card.

Figure 5 shows the Front Panel of spectrum analyzer. The FM signal to be analyzed is picked up by the Rx antenna and is converted into BB by the USRP HW transformer. Its complex envelope is shown by the white (I-component) and red (Q-component) waveforms on the Front Panel. The upper figure in the second column shows the spectrum of received FM signal while the lower one gives the spectrogram.

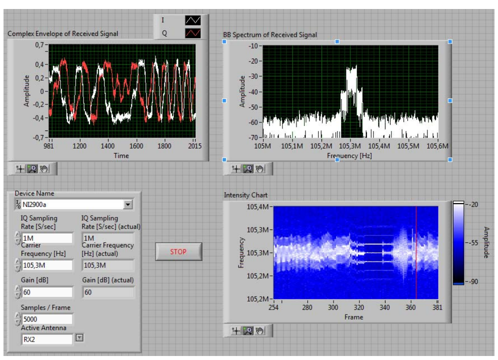

Figure 5. Measuring the spectrum and visualizing the spectrogram.

The Front Panel of the FM receiver is given in Fig. 6. The first picture in the upper row shows the $I-$ and $Q-$components of complex envelope extracted by the USRP HW transformer from the antenna signal. This complex envelope is uploaded to the laptop via the USB cable. The second picture in the upper row gives the spectrum of received FM signal.

The second figure in the lower row gives the spectrum of demodulated signal. Note, both the mono and stereo signal components, and the pilot tone are present. The first picture in the lower row shows the audio signal sent to the audio card and, finally, to the laptop loudspeaker.

C. SDE implementations and testing of a complete radio link

A complete M-ary FSK radio link is implemented at Level 3. As shown in Fig. 2, the Tx RF USRP HW transformer driven by the 4-FSK Tx SW radiates the modulated signal into the air via the Tx antenna. Front Panel of 4-FSK transmitter (laptop, left side) shows the spectrum of transmitted signal. All parameters of FSK transmitter from carrier frequency to FSK frequency deviation can be set via the Tx Front Panel.

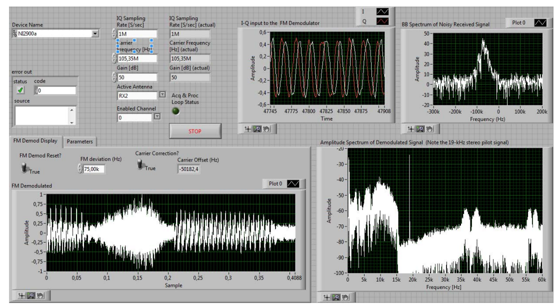

Figure 6. Front Panel of the FM receiver. Audio waveform shown by the first picture in the lower row is sent to the audio card.

The received signal is picked up by the Rx antenna and is converted into a complex envelope by the Rx RF HW Transformer shown on the right side of Fig. 2. This complex envelope is uploaded into the laptop via the USB cable. The Front Panel of 4-FSK receiver (laptop, right side) is used to enter the parameters of FSK receiver and it shows both the spectrum of received signal and the waveform of demodulated FSK signal.

Because real physical RF signals are transmitted and received at Level 3, each channel effect from noise to multipath propagation can be demonstrated in a real application scenario.

D. Software Used to Implement the Different Applications

A part of software used to implement the different applications discussed here is shown in Fig. 7. The complex envelope of 4-FSK signal is generated in baseband by SW and then it is uploaded into the universal HW transformer, that is, into the USRP device via the USB cable with the special driver denoted by "NI-USRP." The USRP device reconstructs the 4-FSK analog microwave signal from the samples of complex envelope.

Figure 7 shows a special feature of SDE implementation. Different functionalities can be implemented by the same complex envelope. For example, the same complex envelope is used in Fig. 7 to generate the transmitted waveform and, simultaneously, to plot its spectrum.

Any programming language that can generate the complex envelope is suitable for the SDE implementation. The graphical programming language used here is easy to learn for the students, and because the universal portable SDE platform can be used everywhere without a laboratory infrastructure, the students can design and test their own ICT system even in a classroom during the discussion of the theory of ICT systems or at home working on assignments or mini projects.

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