Turn your baseband Matlab simulator into a fully functional, 2.4-GHz, operating FM-DCSK transceiver using SDE platform

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***Abstract*—In Software Defined Electronics (SDE), the software and hardware components are completely separated. Every information processing system from communications to measurement engineering is implemented in BaseBand (BB) on a SW platform and the interface between the baseband and RF/microwave domains is assured by a *universal* HW device. Due to the universality of HW device, the implementation of different RF/microwave equipment requires only the change of SW in the application layer.**

Matlab simulators are used to evaluate the feasibility and performance of new signal processing algorithms and equipment everywhere from the academia to industry. This contribution shows how a Matlab BB simulator developed to determine the system performance of an FM-DCSK transceiver can be integrated directly into the SDE platform. The usability and the effectiveness of SDE approach is verified by comparing the simulated BB and measured 2.4-GHz microwave signals.

I. Introduction

The Frequency-Modulated Differential Chaos Shift Keying (FM-DCSK) modulation scheme was published in 1997 [1]. Its robust system performance, offered in both AWGN and noisy multipath channels, has been verified by many authors by means of analytical expressions derived [2]–[5] and computer simulations performed [6], but the excellent predicted system performance has been never verified by real measurements.

The explanation is very simple and straightforward: FM-DCSK differs completely from the conventional digital modulation schemes. Consequently, the integrated circuits available on the market cannot be used to implement an FM-DCSK system, instead, brand new ICs should be developed. The cost of developing a new chip or chipset in this verification phase is so high that every trial launched to implement a real FM-DCSK transceiver has been abandoned.

The advent of Software Defined Electronics (SDE) [7] and high performance universal RF and microwave hardware devices has changed the situation completely. In the SDE approach the HW and SW components are completely separated and only one universal HW device is used to implement any kind of applications from a complete wireless transceiver to a measurement instrument just changing the SW in the application layer.

The idea of HW-SW separation is well known from computer science but until now cheap and universal HW devices offering the high resolution and sampling rate required in the RF and microwave engineering have not yet been available.

In the SDE approach not the RF and microwave bandpass signals but their complex envelopes [8] are processed in the BaseBand (BB). The radio transceiver or measurement instrument are implemented in BB, the former and latter are referred to as Software Defined Radio (SDR) and Virtual Instrumentation (VI), by using the baseband equivalent of a RF or microwave system. The crucial advantage of the equivalent BB representation is that the required sampling rate is determined by the bandwidth of bandpass RF/microwave signal to be processed and that the center frequency of RF/microwave bandpass signal has no influence on the required sampling rate.

In software defined electronics

- the entire transceiver or measurement equipment are implemented in BB on a SW platform and
- a universal RF hardware device is used to reconstruct the analog bandpass RF/microwave signal from its complex envelope and to extract the complex envelope from the received RF/microwave bandpass signal at the transmit and receive sides, respectively.

There is one more thing why the SDE approach can be easily integrated into the up-to-date computer simulators. To reduce the simulation time the up-to-date simulators use exclusively complex envelopes and not the real-time RF/microwave signals. Since the universal HW devices also rely on and process the complex envelopes, with appropriate modifications, the complex envelopes processed by the BB computer simulators can be directly uploaded to or received from the universal HW device.

To verify the system performance of FM-DCSK over AWGN and noisy multipath channels we have developed a computer simulator [6] much before the advent of SDE approach. The simulator developed works on the complex envelopes. This contribution shows

- how an FM-DCSK system can be implemented in the baseband and
- how a computer simulator relying on the complex envelopes can be integrated directly into the SDE approach.

The theoretical considerations are verified by the implementation of an FM-DCSK transceiver and the signals, both in the BB and in the 2.4-GHz microwave frequency region, are shown and compared.

Recall, both the radio communications and measurement engineering are about the signal analysis. The only difference is that different kinds of information are extracted in a radio receiver to perform the demodulation and in a test equipment. The SDE approach makes the simultaneous implementation of both functions possible, one algorithm demodulates the received signal, while the other, for example, evaluates the spectrum of received signal in order to determine the channel conditions. Since the two algorithms are run parallel, the demodulation and channel measurement can be done simultaneously, consequently, the channel conditions can be measured without interrupting the data communications.

II. Theoretical background: Complex envelope and equivalent baseband model

1) Definition of complex envelope: Consider a bandpass, typically but not necessarily RF/microwave signal $x(t)$ with an RF bandwidth of $2B$ centered about a center frequency f_c with its Fourier transform $X(f)$. The spectrum of this bandpass signal is depicted in Fig. 1(a).

To get a BB signal, $X(f)$ should be shifted to zero-frequency. Unfortunately, this cannot be done in one step because every real-valued physical signal $x(t)$ has a two-sided spectrum.

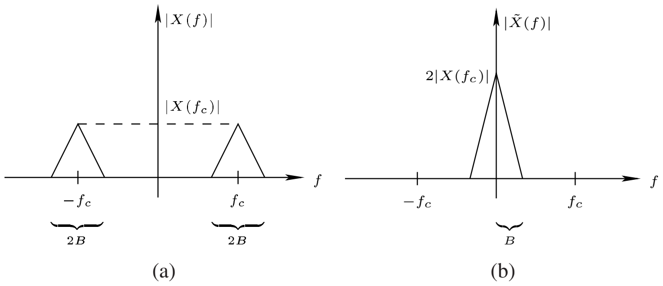

Fig. 1. Spectra of the (a) bandpass RF/microwave signal $x(t)$ and (b) its complex envelope $\tilde{x}(t)$.

Introducing the Hilbert transform [8], a pre-envelope $x_+(t)$ can be defined that possesses a one-sided spectrum. Then the one-sided spectrum of pre-envelope is shifted to zero-frequency to get the spectrum $\tilde{X}(f)$ of complex envelope that is shown in Fig. 1(b). Note, the complex envelope $\tilde{x}(t)$ is a low-pass signal. Every bandpass signal can be fully characterized by its complex envelope provided that the half of its RF bandwidth does not exceed the center frequency.

The use of complex envelope offers the following features:

- Except the center frequency f_c, the complex envelope $\tilde{x}(t)$, given in BB, carries all the information carried by the original RF/microwave bandpass signal.
- It is a *representation*, i.e., the RF bandpass signal can be fully reconstructed, without any distortion, from its complex envelope.
- The complex envelope assures the attainable minimum sampling rate that is equal to $2B$, i.e., the RF/microwave bandwidth.

The price that has to be paid for the BB representation and minimum sampling rate is that the complex envelope $\tilde{x}(t) = x_I(t) + jx_Q(t)$ is not a real- but a *complex-valued* signal where $x_I(t)$ and $x_Q(t)$ are referred to as the in-phase and quadrature components and are identified by the letters "I" and "Q", respectively. Note, not only the bandpass signals but every bandpass LTI system and Gaussian random process have their BB equivalent [8].

2) Transformation between the RF/microwave and BB domains: Very simple transformations establish the relationship between the bandpass RF/microwave signals and their BB representations. Figure 2 shows, as an example, the extraction of complex envelope $\tilde{x}(t)$ from a RF/microwave bandpass signal $x(t)$ in the time domain. For more details refer to [8] or [7].

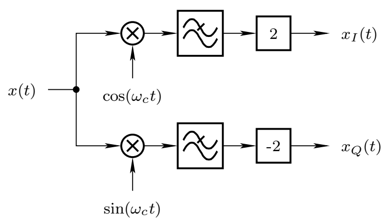

Fig. 2. Extraction of complex envelope $\tilde{x}(t) = x_I(t) + jx_Q(t)$ from a bandpass RF/microwave signal $x(t)$.

3) BB equivalent of an FM-DCSK transceiver: The BB equivalent of an FM-DCSK transceiver was developed in [9]. The BB model is depicted in Fig. 3 where $m(t)$ is a chaotic signal, b_k denotes the *bit stream to be transmitted*, $\tilde{x}(t) = s_I(t) + js_Q(t)$ is the complex envelope of *transmitted FM-DCSK signal*, K denotes the channel attenuation, $n_I(t)$ and $n_Q(t)$ are the in-phase and quadrature components of channel noise, $h_I(t) = \tilde{h}(t)$ denotes the complex impulse response of channel filter, $\tilde{r}(t) = r_I(t) + jr_Q(t)$ is the *received signal* selected by the channel filter, and $z(t)$ denotes the *observation signal* used by the decision circuit to make an estimation for the transmitted bit. This BB model was used to develop a BB simulator implemented in Matlab [6].

In our Matlab BB simulator separate subroutines were used to model the behavior of the constituting blocks of a FM-DCSK transceiver. The constituting blocks and their inputs/outputs are marked in Fig. 3.

III. The universal HW device

Recall, BB simulators rely on complex envelopes exclusively. There are a few universal HW devices available on the market that convert the complex envelope into a bandpass RF/microwave signal and extract the complex envelope from a received bandpass RF/microwave signal at the transmit and receive side, respectively. One example is the Universal Software Radio Peripheral (USRP) [10] which is suitable for the implementation of an embedded system where the USRP constitutes the physical layer defined in the OSI BR model [11]. The USRP devices offers two Service Access Points (SAPs) at both the transmit and receive sides [7]:

- SAP for the USRP management service to set the USRP parameters such as gain, carrier frequency, etc.;
- SAP for the USRP data service to transfer the I/Q components of complex envelope.

The USRP drivers provide access to the two SAPs. These drivers will be used in the next section to turn our Matlab BB simulator into a fully operational 2.4-GHz FM-DCSK transceiver.

IV. Implementation of an FM-DCSK transceiver

A graphical data-flow type programming language has been chosen to integrate the BB Matlab simulator and to implement the drivers for the transmit and receive USRP units. Its duties are threefold:

1) to provide access to the USRP HW via its drivers,
2) to integrate the Matlab simulator,
3) to visualize the BB signals measured in the FM-DCSK transceiver either in the time- or in the frequency domain.

To show the details of implementation, the integration of Matlab BB simulator and the GUI developed to visualize the signals will be shown at the transmit and receive sides, respectively.

1) Integration of Matlab simulator: Figure 4 shows the integration of Matlab BB simulator at the transmit side. The *Matlab script window* runs the Matlab SW engine in background and provides an interface to pass or share BB signals and information between the two platforms. The algorithms used in Matlab BB simulator to implement the *FM modulator* and *DCSK mod* blocks of the FM-DCSK modulator, furthermore, the *AWGN channel* can be recognized in the Matlab script window. Note, these algorithms implement the blocks of BB equivalent of FM-DCSK transmitter and AWGN radio channel depicted in Fig. 3.

Figure 4 shows the three main steps of implementation. The Matlab BB simulator generates the in-phase, see "ModI_LV" in Fig. 4, and quadrature, see "ModQ_LV" in Fig. 4, components of complex envelope of the modulated FM-DCSK signal to be transmitted, then the complex envelope and its sampling frequency is bundled into a cluster by the *IQ data to USRP* block, finally this cluster is uploaded

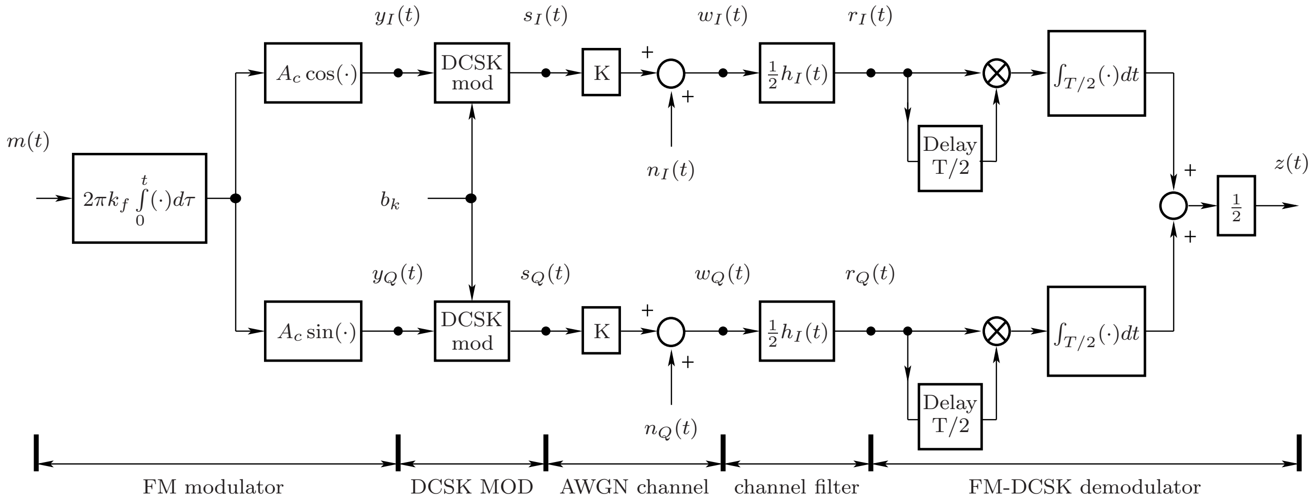

Fig. 3. BB equivalent of an FM-DCSK transceiver. Note the constituting blocks and their inputs/outputs in baseband.

into the USRP device via *USRP data SAP*. The 2.4-GHz bandpass microwave signal is reconstructed by the USRP device.

To verify the SDE approach, let the spectrum of an FM-DCSK signal generated by the Matlab in *baseband* be compared against the microwave spectrum measured at the USRP RF connector by an Agilent stand-alone spectrum analyzer.

The FM-DCSK signal has a comb-like spectrum when a pure bit "1" sequence is transmitted. This spectrum, determined by Matlab in baseband is shown in Fig. 5.

In the next step, according to the SDE approach shown in Fig. 4, the FM-DCSK transmitter was implemented. The spectrum of the 2.4-GHz modulated FM-DCSK signal measured by the stand-alone spectrum analyzer is shown in Fig. 6. Note, the two spectra are identical, verifying the usability of the SDE approach.

2) FM-DCSK receiver: The GUI showing the signals in the FM-DCSK receiver is shown in Fig. 7. Top left and right figures show I/Q components of BB signal, denoted by $r_I(t)$ and $r_Q(t)$ in Fig. 3, in the time domain and the power spectrum of complex envelope, respectively, when a noisy FM-DCSK signal carrying a random bit stream is received. Bottom left figure visualizes the observation signal generated by the autocorrelation FM-DCSK detector. This signal, denoted by $z(t)$ in Fig. 3, is used by the timing recovery and decision algorithms to perform the demodulation. The observation signal at the decision time instants is shown in bottom right figure.

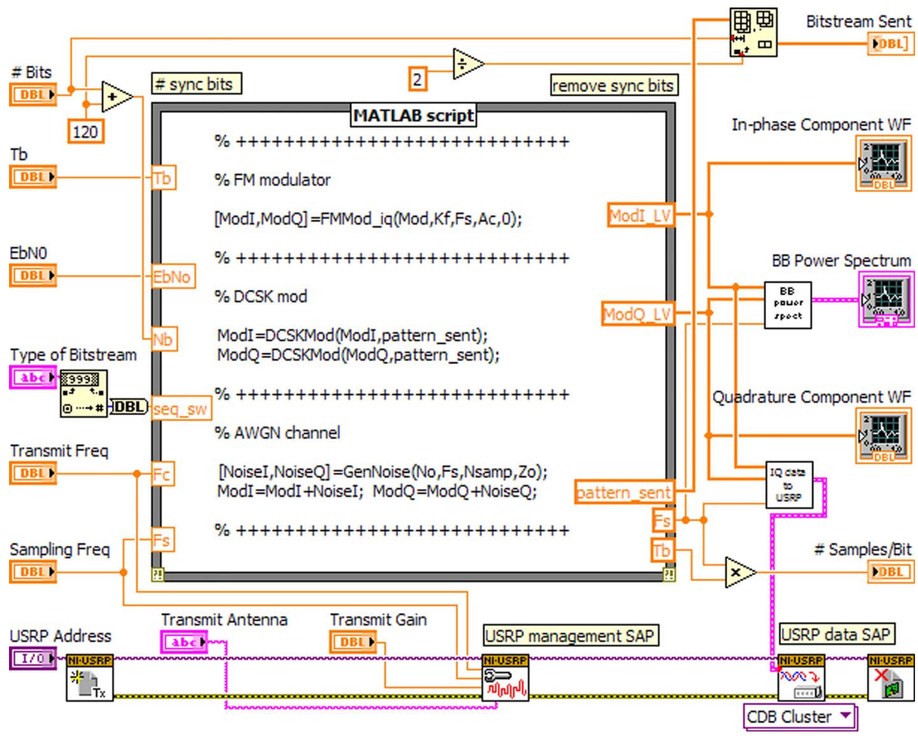

Fig. 4. Transmit side: Integration of BB Matlab simulator.

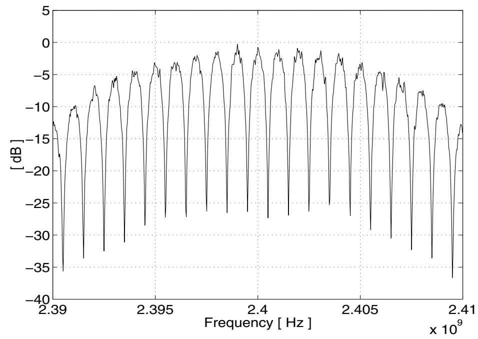

Fig. 5. Matlab BB simulator: Spectrum of FM-DCSK signal with data rate of 500 kHz when a pure bit “1” sequence is transmitted. Note, this spectrum has been determined in baseband by Matlab.

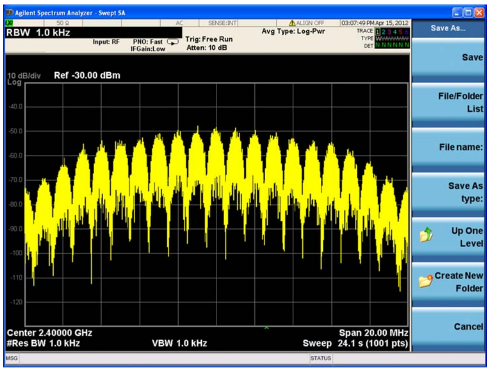

Fig. 6. Agilent stand-alone spectrum analyzer: Spectrum of FM-DCSK signal with a data rate of 500 kHz when a pure bit “1” sequence is transmitted.

Note, not only an FM-DCSK receiver but even a spectrum analyzer can be implemented. This property of SDE approach makes the observation of channel conditions possible without the interruption of communications. This feature is essential in cognitive radio and in many other applications where a continuous monitoring of equipment or radio channel has to be performed.

V. Conclusions

The advent of software defined electronics makes the implementation of any bandpass RF/microwave communications and measurement systems and signal processing algorithm possible in baseband and assures the use of theoretically attainable lowest sampling rate. In SDE, every signal processing task is performed in BB and the transformations between the BB and RF/microwave regions are performed by a universal HW device. The implementation of a new application requires only the change of SW in the application layer.

Matlab is used everywhere to evaluate the feasibility and performance of a new information processing system. This contribution has shown how a Matlab BB simulator can be integrated into the SDE approach. The usability of integration has been verified by comparing the spectra of simulated and measured signals.

An important feature of SDE approach is that different signal processing algorithms using the same signals can be run parallel. This feature, for example, makes the monitoring of a radio channel and performing the demodulation possible simultaneously, without the interruption of reception.

Acknowledgment

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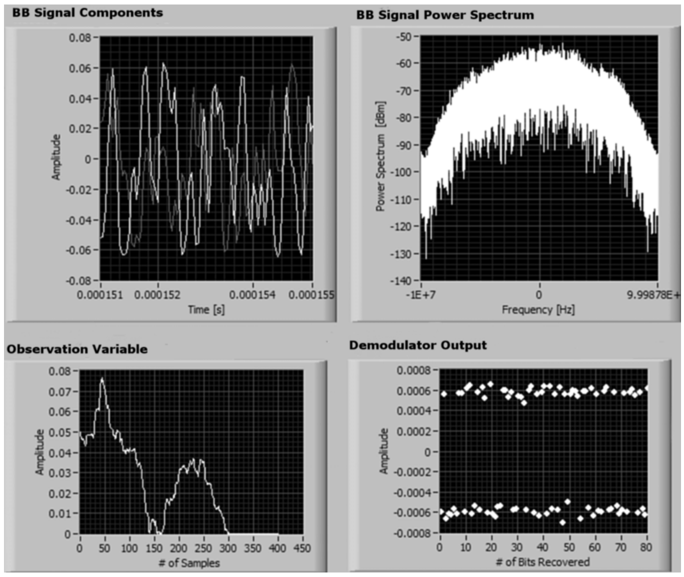

Fig. 7. Waveforms in the FM-DCSK receiver implemented on the SDE platform. The complex envelope of the received noisy 2.4-GHz microwave signal is extracted by the USRP device and all waveforms are processed by Matlab in baseband.

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